SOME STUDIES OF A FLOATING LID TYPE DEVICE FOR SUPPRESSION OF LIQUID SLOSHING IN RIGID CYLINDRICAL TANKS

by

H. Norman Abramson
Guido E. Ransleben, Jr.

Technical Report No. 10
Contract No. DA-23-072-ORD-1251
SwRI Project 43-768-2

1 May 1961

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS

[illegible]
[illegible]
[illegible]
SLOSHING IN [illegible]
1 May 61, 1/6 [illegible]

ONE TYPE OF SUPPRESS[illegible] [illegible] ALLY CONSTRAINS THE LIQUID [illegible] THE LONGI- TUDINAL AXIS OF THE TANK. [illegible] WITH THE LIQUID AS THE TANK DRAINS SO AS TO REMAIN [illegible] CONTACT WITH THE LIQUID FREE SURFACE. THE PURPOSE OF THE INVESTIGATION IS TO OBTAIN DATA ON THE EFFECTIVENESS OF SUCH FLOATING LID DEVICES IN SUPPRESSING LIQUID SLOSHING IN RIGID CYLINDRICAL TANKS HAVING A CONICAL BOTTOM. THE LIDS THEMSELVES WERE FABRICATED FROM SOLID PLATES RIGIDLY SUPPORTED ON THREE DYNAMOMETER ARMS, IN ORDER TO OBTAIN DATA ON THE LIQUID FORCES ACTING DIRECTLY ON THE LIDS.

Poor quality
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Department of Mechanical Sciences
Engineering Analysis Section

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Prepared for

U. S. Army Ordnance Missile Command
Army Ballistic Missile Agency
Redstone Arsenal, Alabama

1 May 1961

APPROVED

H. Norman Abramson

H. Norman Abramson, Director
Department of Mechanical Sciences

INTRODUCTION

Suppression of liquid propellant sloshing in rocket tanks has largely been accomplished by means of various arrangements of fixed baffles and "floating can" type devices (1).* Another interesting type of suppression device is that of a "lid" which essentially constrains the liquid surface to remain plane and normal to the longitudinal axis of the tank; such a device must, of course, move with the liquid as the tank drains so as to remain always just in contact with the liquid free surface.

The purpose of the investigation reported here was to obtain data on the effectiveness of such floating lid devices in suppressing liquid sloshing in rigid cylindrical tanks having a conical bottom. The test facilities and procedures employed were essentially those described in our earlier publication (1). The lids themselves were fabricated from solid plates rigidly supported on three dynamometer arms, in order to obtain data on the liquid forces acting directly on the lids, and had diameters of approximately 99, 85, and 67% of the tank diameter (Figure 1).

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* Numbers in parenthesis refer to the References given at the end of the paper.

The support system was clamped to the tank so that the lids barely touched the surface of the undisturbed liquid which, in these tests, were water, methylene bromide, and methylene chloride. Each lid-liquid combination was tested at various excitation amplitudes and frequencies.

EXPERIMENTAL RESULTS

Measured data for the total force response resulting from translational excitation of amplitude X_o with the three different lids is given in Figures 2 - 17. The data is presented in terms of dimensionless force amplitude and phase angle ϕ as a function of the dimensionless frequency parameter $\omega^2 d/a$, where d is the tank diameter, h is the liquid depth, and a is the axial acceleration, as employed previously (1). Data for the lid having a diameter 99% of that of the tank is given in Figures 2 - 7 and shows that almost infinite damping of the total force response is provided at all liquid depths, there being virtually no peaking of the force curve. Such a linear variation of force response with the square of the frequency corresponds precisely, of course, with the results of theoretical predictions for a liquid

with the free surface constrained to remain plane and normal to the longitudinal axis of the tank. The 85% lid (Figures 8 - 13) appears to introduce damping with a magnitude approximately equivalent to that provided by the conical ring fixed baffle type of suppressors (1), although actual damping coefficients have not been calculated. The peak magnitude is seen to vary with both liquid viscosity and excitation amplitude as the liquid first mode resonant frequency is increased from $\omega^2 d/a = 3.6$ with no lid to $\omega^2 d/a = 5.0$ with lid. The 67% lid introduces very little damping, as evidenced by the magnitude of the peak forces (Figures 14 - 17). The liquid first mode resonant frequency however, appears to be slightly increased over that with no lid.

The orientation of the dynamometers attached to the lids for the purpose of obtaining data on the liquid forces acting on the lid is shown in Figure 18. One more or less representative plot of the forces on the lid is shown in Figure 19. Most of the lid dynamometer data is somewhat questionable because of instrumentation difficulties and therefore this data is presented only to show orders of magnitude and frequency response trends.

Total force response data from similar tests with the excitation provided by pitching* about the liquid c. g. is shown in Figures 20 - 33. Data for the 99% lid is given in Figures 20 - 24, and shows similar trends to that for the tests with translational excitation. The theoretical curves shown in some of these figures correspond to an ideal liquid with no suppression device (1), as a matter of general interest. The 85% lid data (Figures 25 - 29) and the 67% lid data (Figures 30 - 33) also show trends very similar to that for the tests with translational excitation.

CONCLUSIONS

The results of these tests would seem to lead to the following general conclusions:

1. Floating lid type devices having a diameter of 85%, or more, of the tank diameter are quite effective in providing increased damping of the peak total force response. A 67% lid provides almost no damping at all.

---

* Other studies of sloshing characteristics in rigid cylindrical tanks undergoing pitching motions are given in (2) and (3).

2. The peak force responses with the 85% lid decrease with increasing excitation amplitude, but increase slightly with increasing equivalent Reynolds' number of the test liquid. This is accompanied by a pronounced increase in the liquid first mode resonant frequency.

3. The forces acting directly on the lids appear to be rather large so that such devices may well prove to involve significant weight penalties for the damping provided.

REFERENCES

1. Abramson, H. N. and Ransleben, G. E., Jr., "Simulation of Fuel Sloshing Characteristics in Missile Tanks by Use of Small Models," ARS Journal, 30, 7, pp. 603-612, July 1960.

2. Abramson, H. N. and Ransleben, G. E., Jr., "Total Force Response Resulting From Liquid Sloshing in a Rigid Cylindrical Tank with a Vertical Center Wall Baffle," Tech. Rept. No. 9, Contract No. DA-23-072-ORD-1251, Southwest Research Institute, May 1961.

3. Abramson, H. N. and Ransleben, G. E., Jr., "Liquid Sloshing in Rigid Cylindrical Tanks Undergoing Pitching Motion," Tech. Rept. No. 11, Contract No. DA-23-072-ORD-1251, Southwest Research Institute, May 1961.

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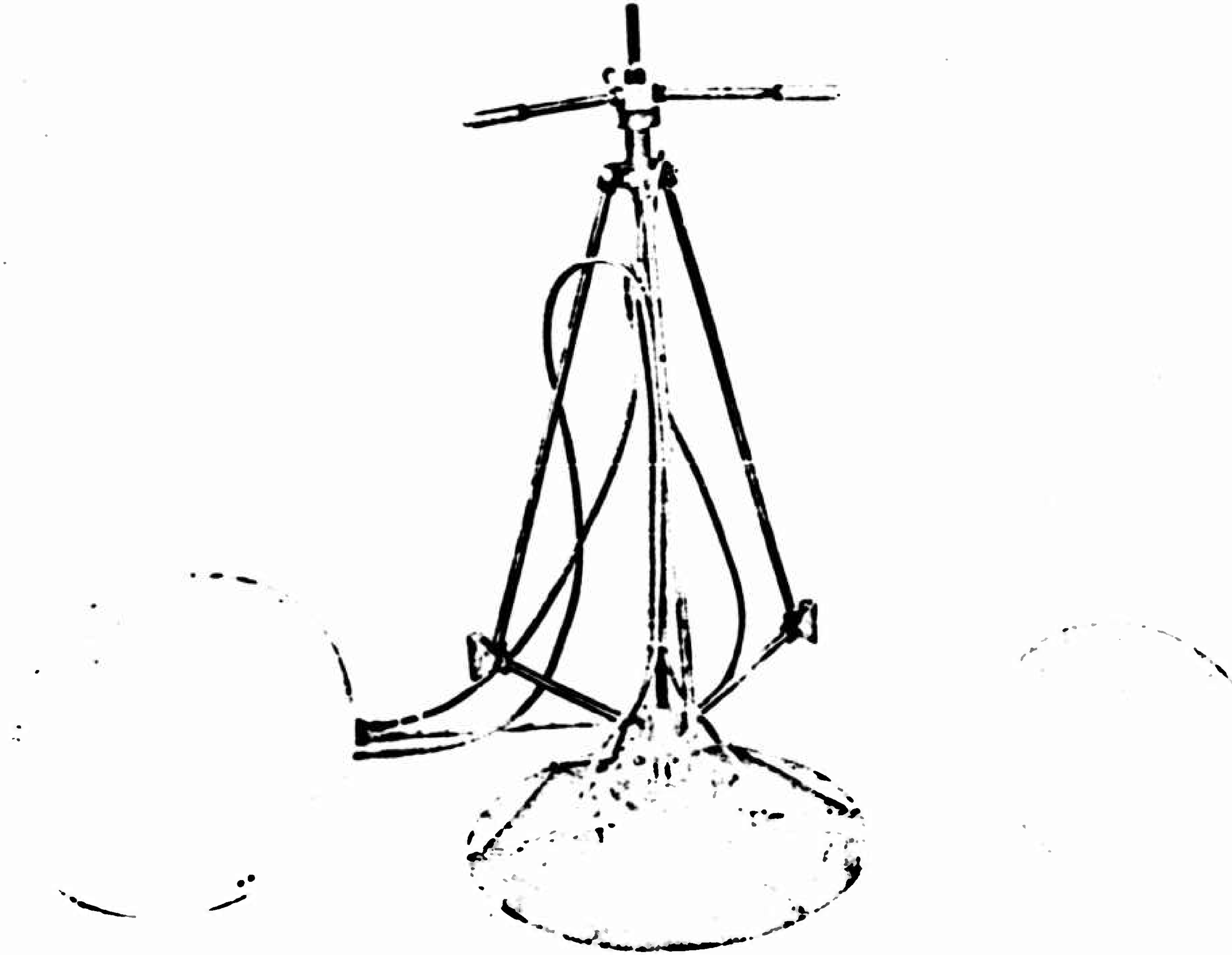


Figure 1. Simulated Lids and Support Assembly

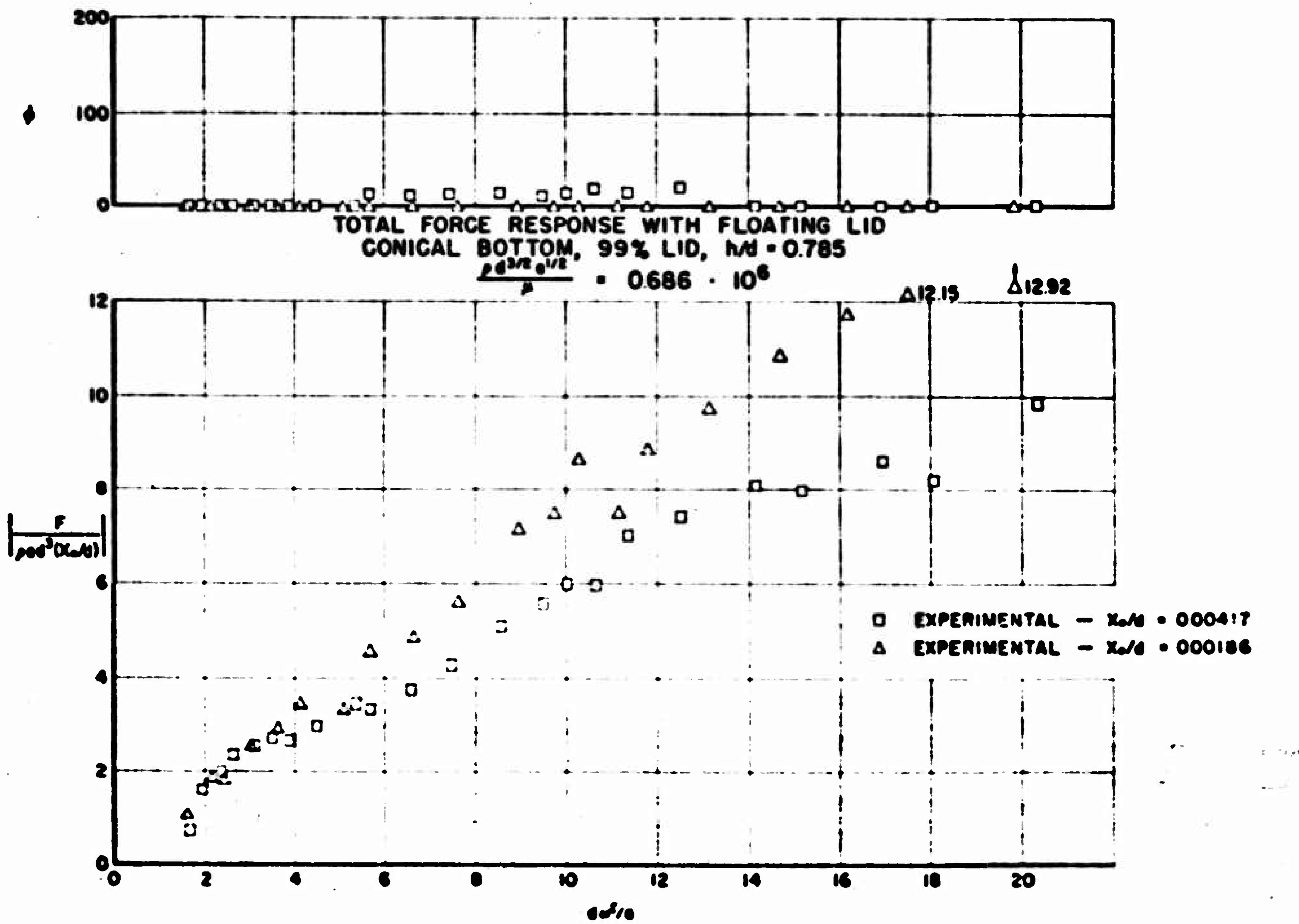
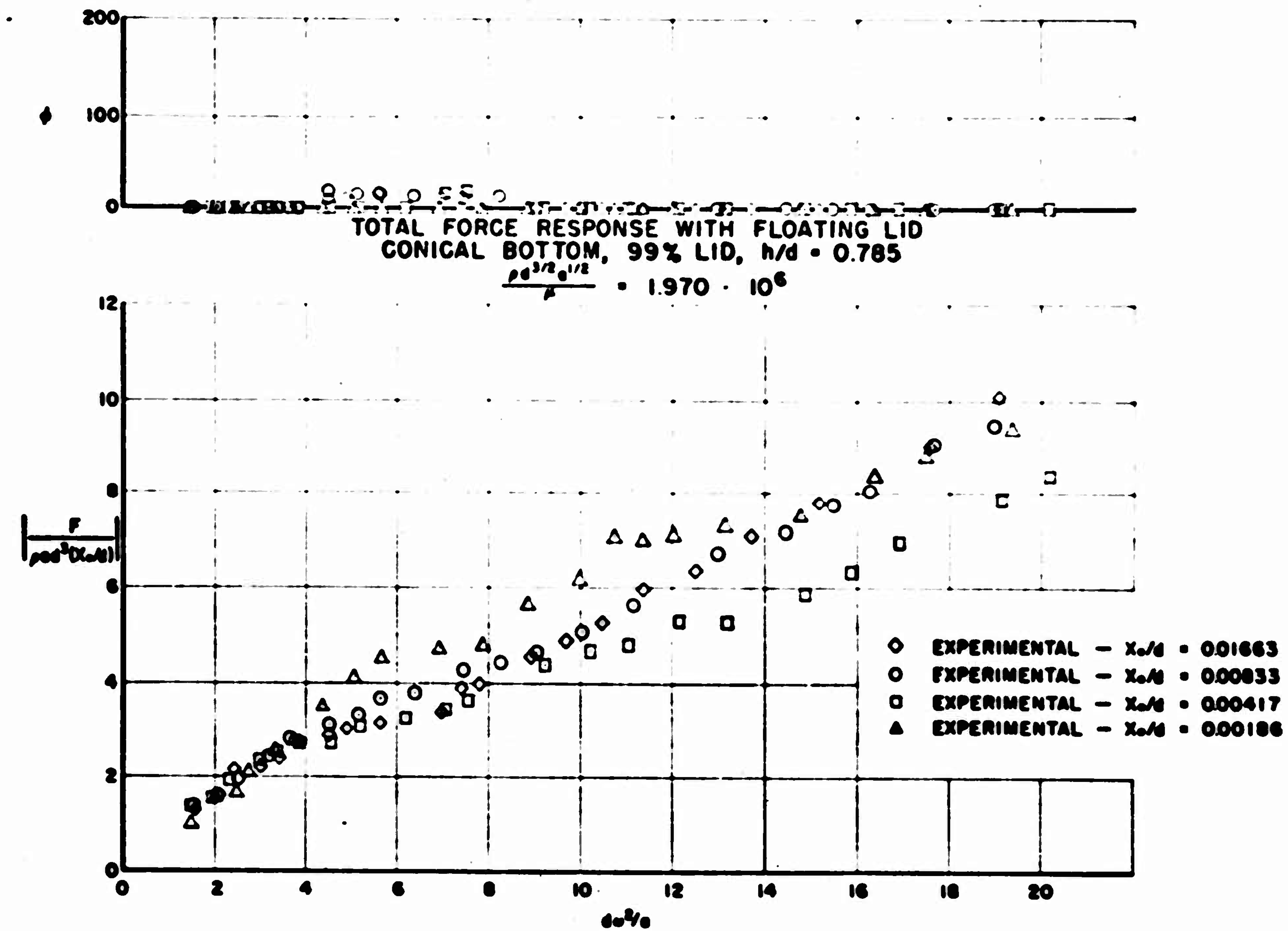
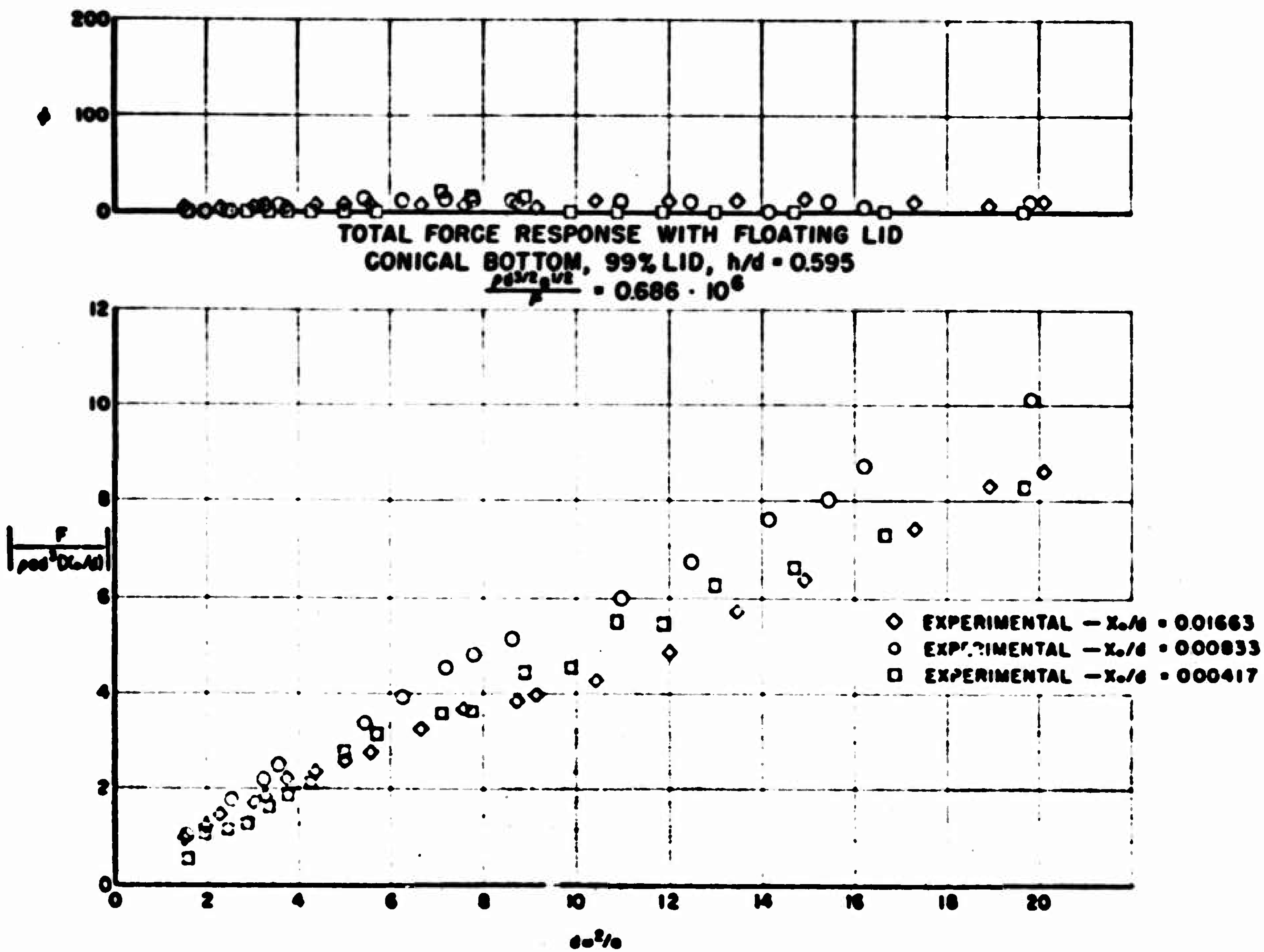

200
100
ϕ
0
TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 99% LID, h/d = 0.785
$\frac{\rho d^{3/2} g^{1/2}}{\mu}$ = 0.686 · 10^6
12
10
8
6
4
2
0
$\left|\frac{F}{\rho g d^3 (X_o/d)}\right|$
Δ12.15
Δ12.92
EXPERIMENTAL — X_o/d = .000417
EXPERIMENTAL — X_o/d = .000186
0
2
4
6
8
10
12
14
16
18
20

Figure 2.



TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 99% LID, h/d = 0.785
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
ϕ
200
100
0
12
10
8
6
4
2
0
$\left|\frac{F}{\rho g d^3 (X_o/d)}\right|$
0
2
4
6
8
10
12
14
16
18
20
EXPERIMENTAL — X_o/d = 0.01663
FXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417
EXPERIMENTAL — X_o/d = 0.00186

Figure 3.



TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 99% LID, h/d = 0.595
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 0.686 \cdot 10^6$
EXPERIMENTAL — X_o/d = 0.01663
EXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417

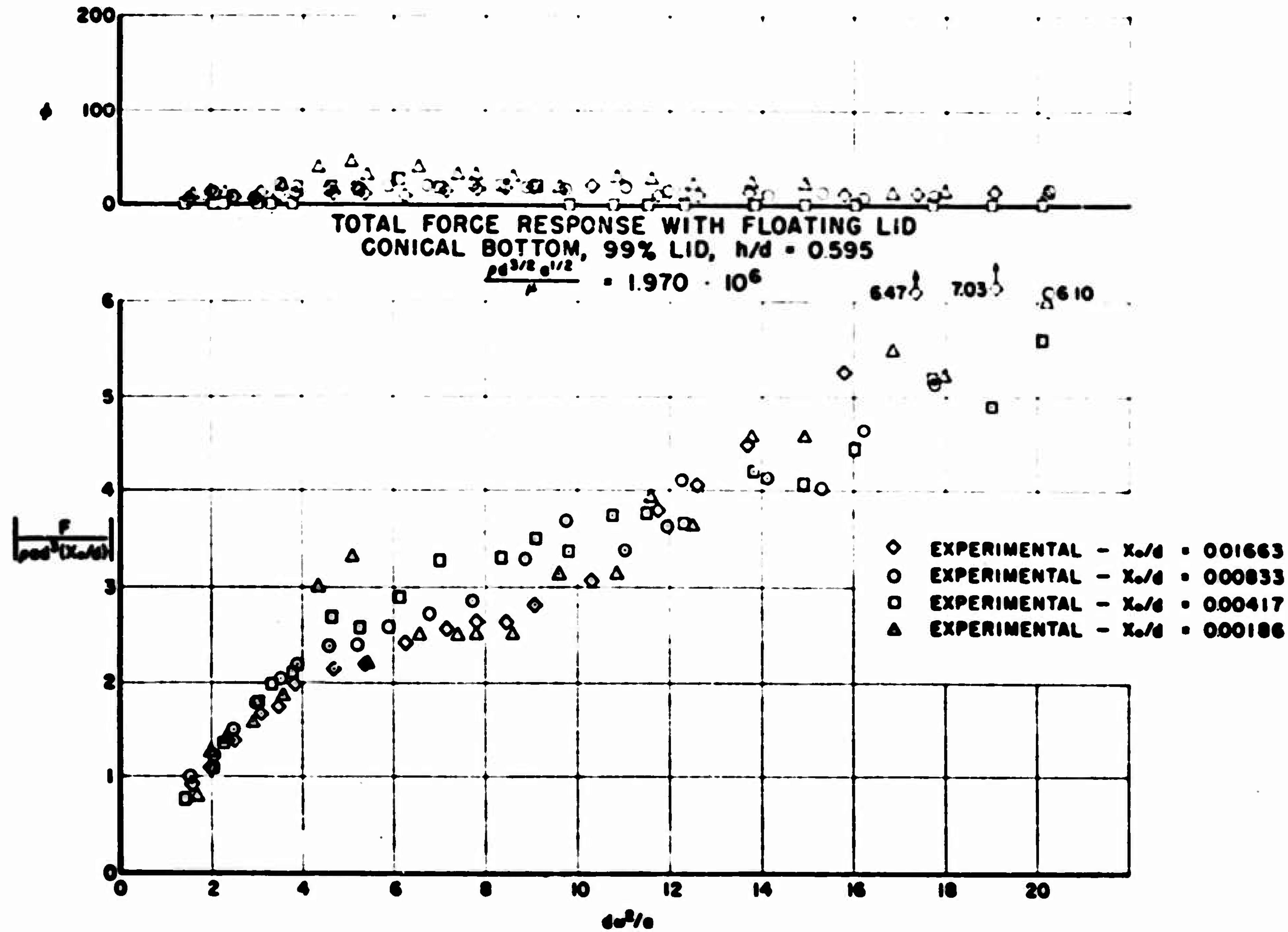
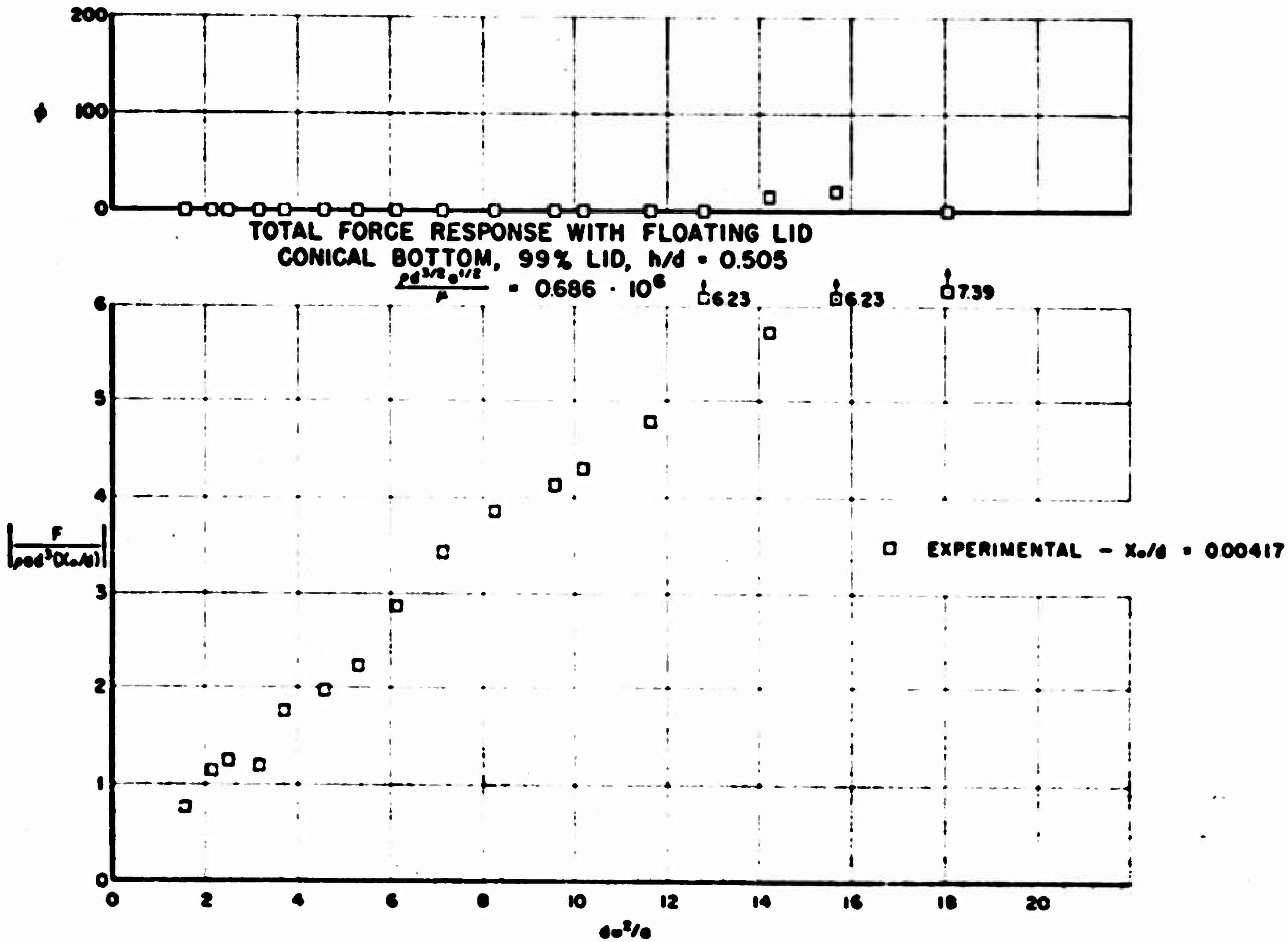

TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 99% LID, h/d = 0.595
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
EXPERIMENTAL − X_o/d = .001663
EXPERIMENTAL − X_o/d = .000833
EXPERIMENTAL − X_o/d = .000417
EXPERIMENTAL − X_o/d = .000186
6.47
7.03
6.10
ϕ
$\frac{F}{\rho g d^3 (X_o/d)}$
$d\omega^2/g$

Figure 5.



TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 99% LID, h/d = 0.505
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 0.686 \cdot 10^6$
6.23
6.23
7.39
ϕ
200
100
0
6
5
4
3
2
1
0
$\left|\frac{F}{\rho\omega d^3 (X_o/d)}\right|$
EXPERIMENTAL – X_o/d = 0.00417
0
2
4
6
8
10
12
14
16
18
20
$d\omega^2/g$

Figure 6.

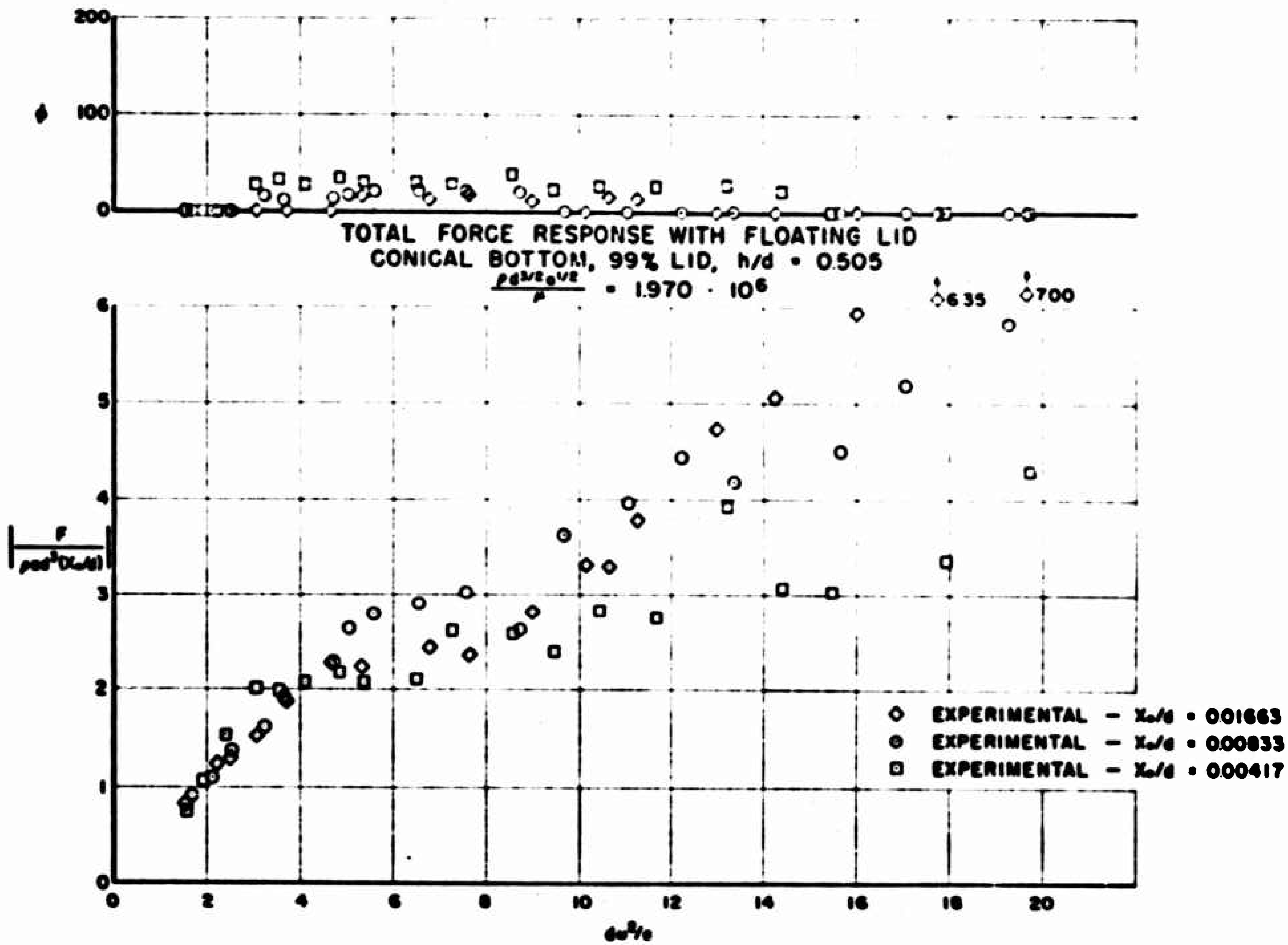
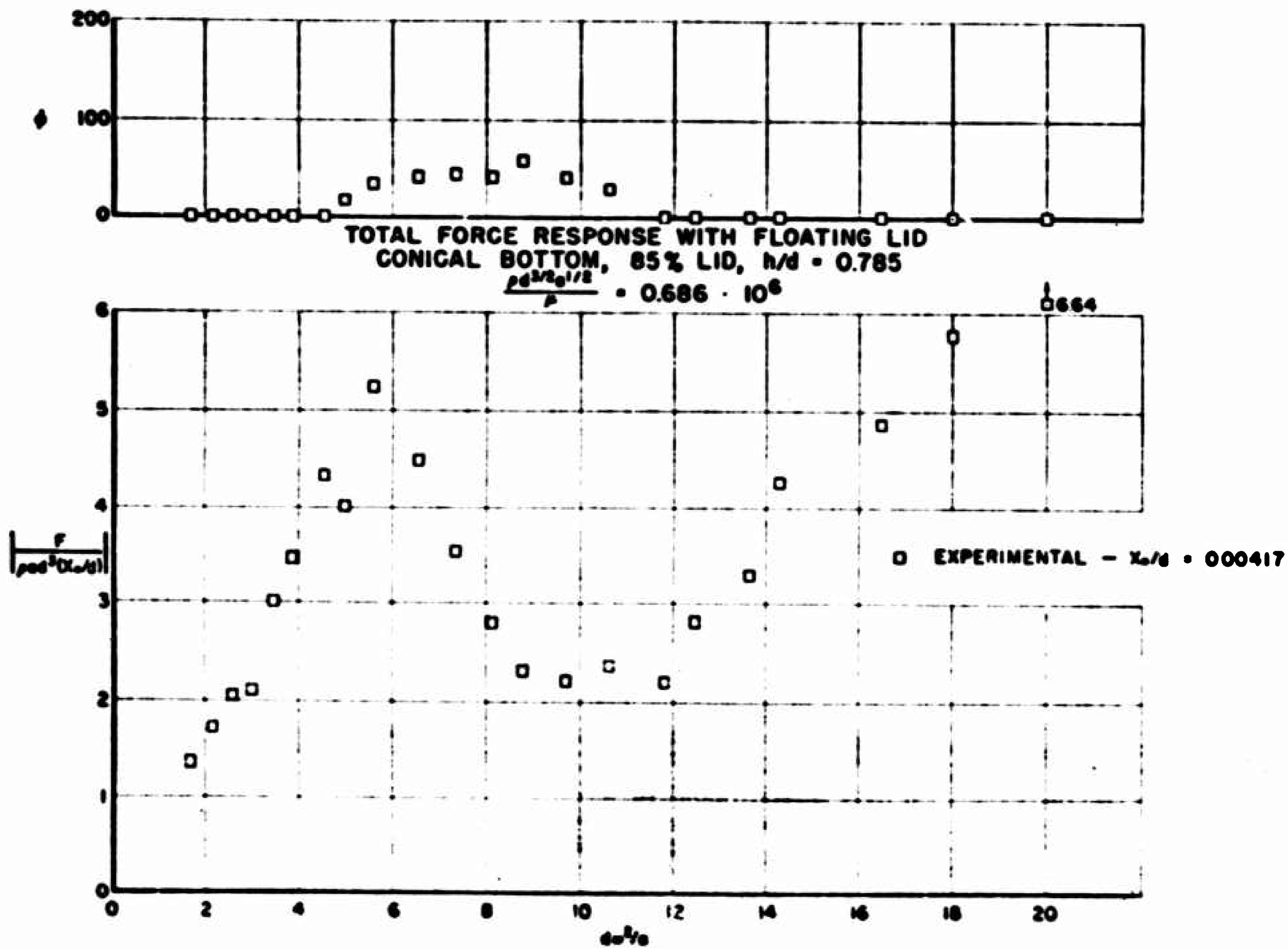

TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 99% LID, h/d = 0.505
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
635
700
EXPERIMENTAL — X_o/d = 0.01663
EXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417
0
2
4
6
8
10
12
14
16
18
20
100
200
1
3
5
ϕ
$\frac{F}{\rho g d^3 (X_o/d)}$

Figure 7


TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 85% LID, h/d = 0.785
= 0.686 · 10^6
EXPERIMENTAL — X₀/d = 000417
664

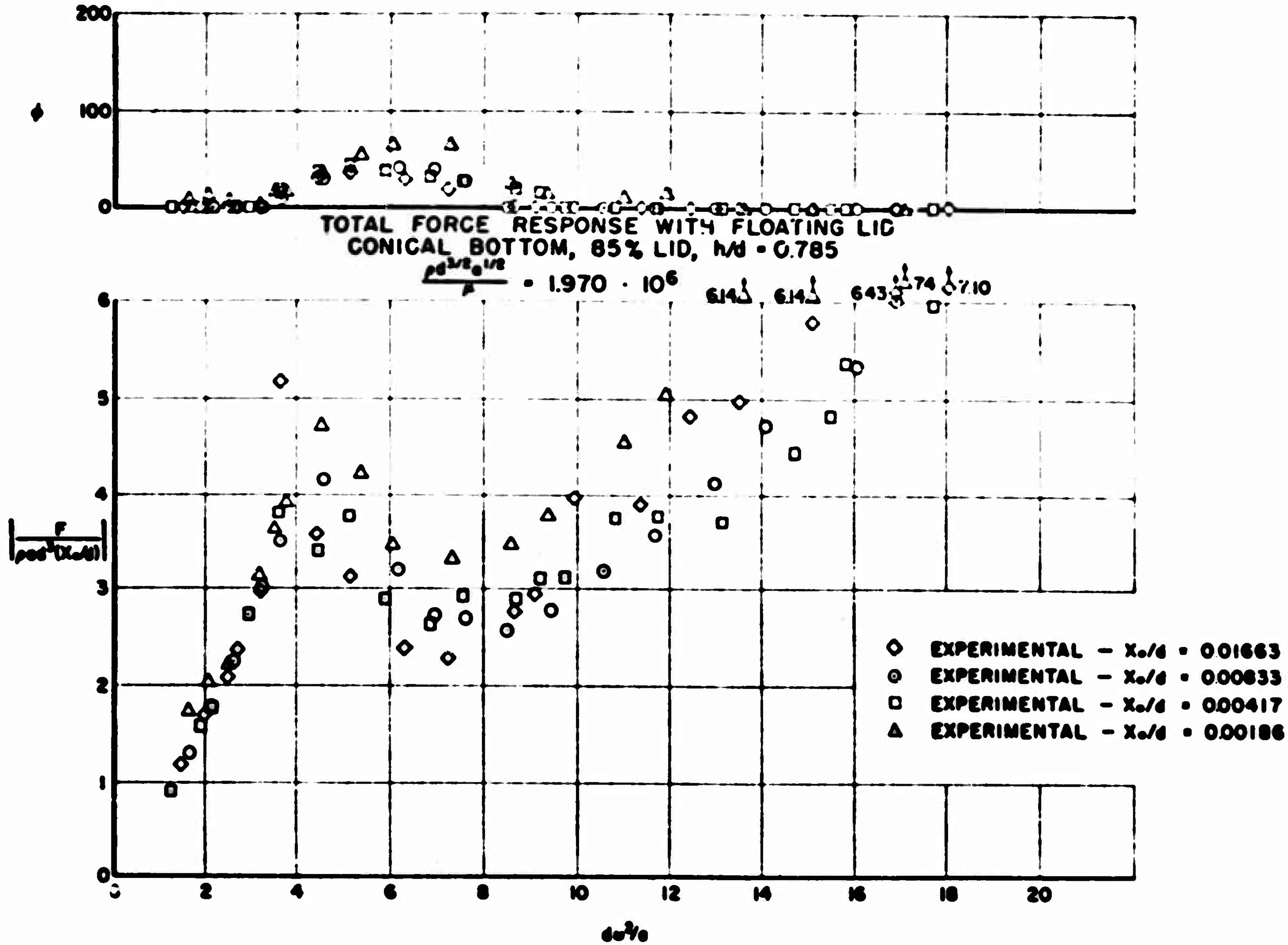
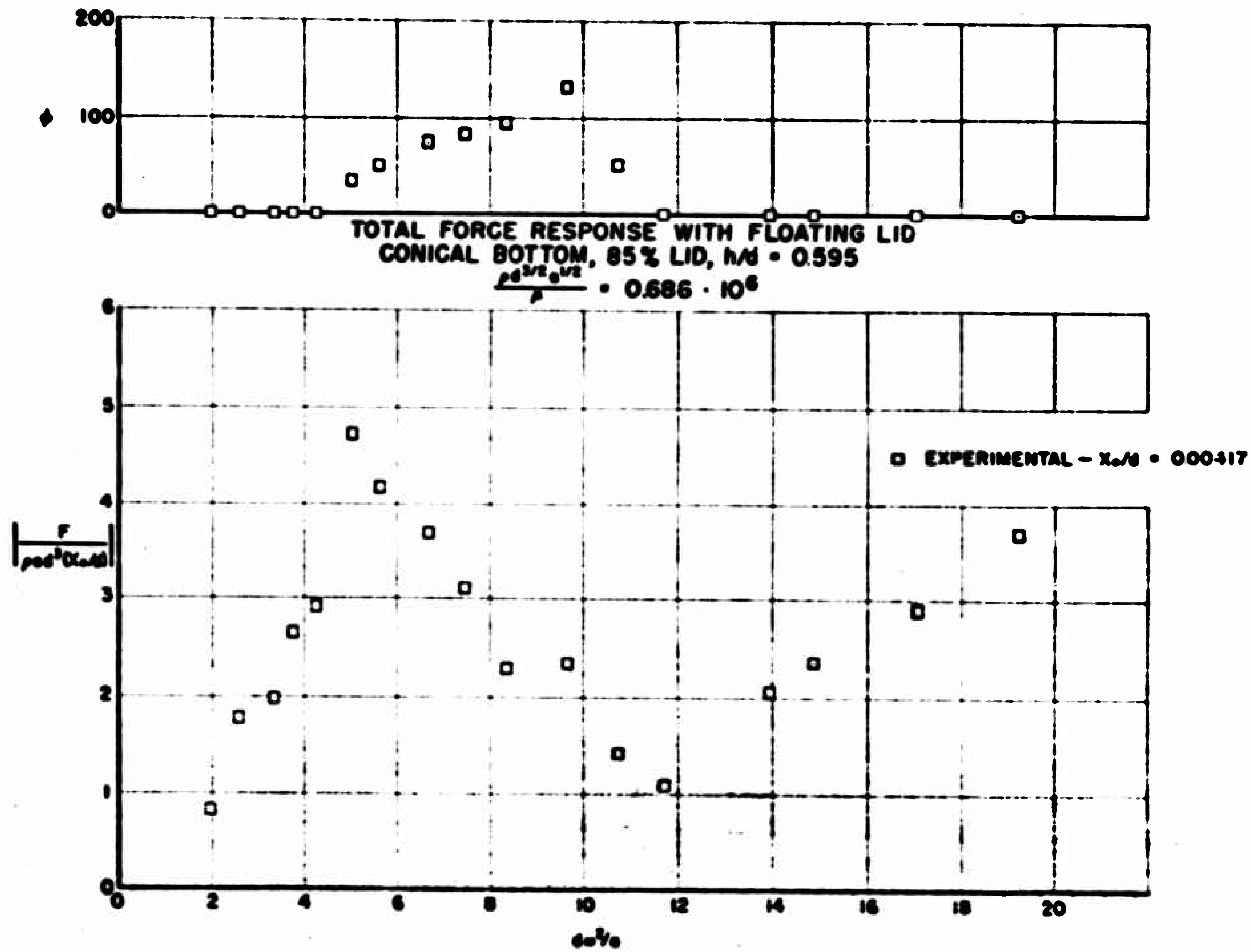
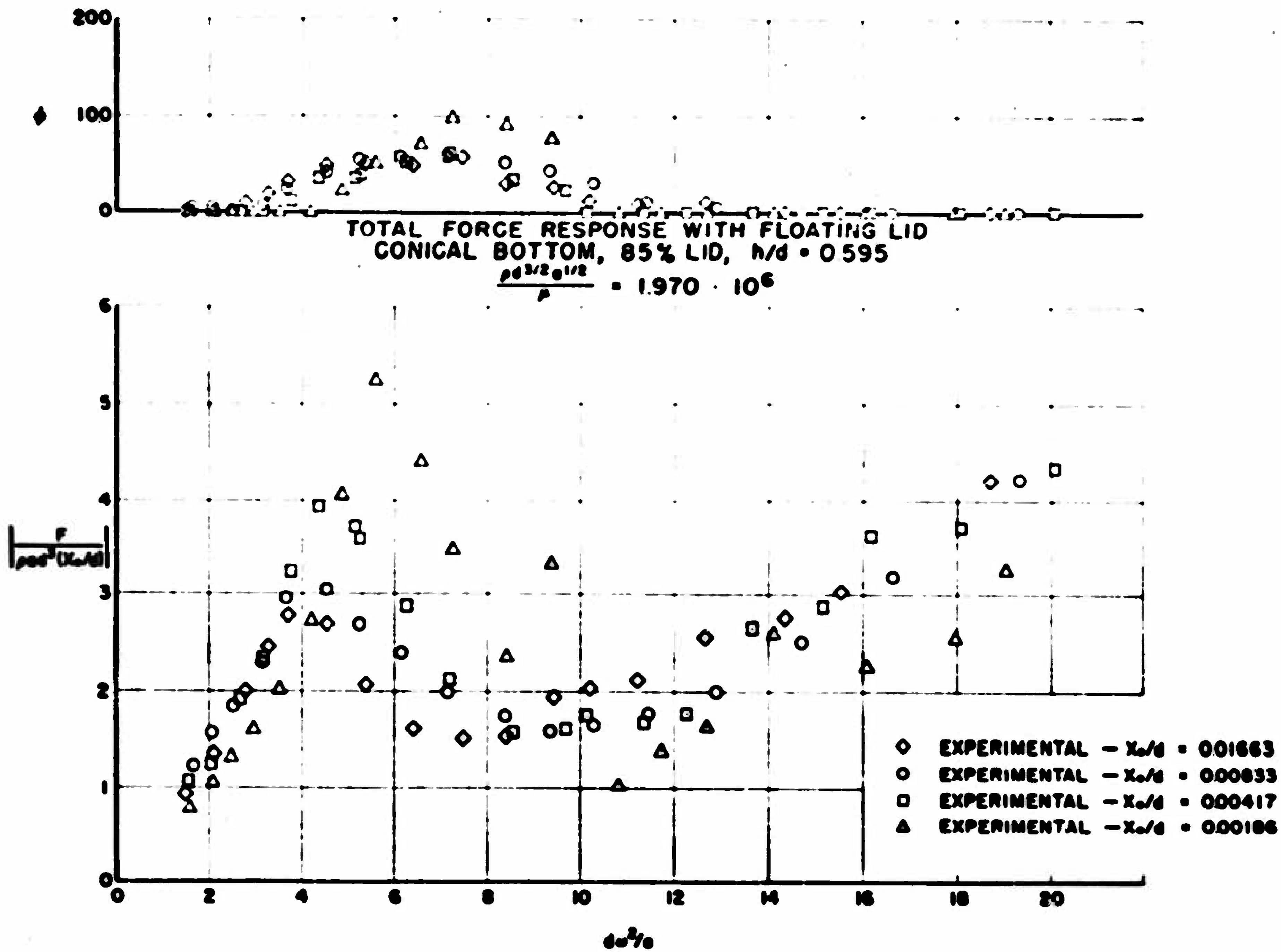

TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 85% LID, h/d = 0.785
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
EXPERIMENTAL — X_o/d = 0.01663
EXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417
EXPERIMENTAL — X_o/d = 0.00186
ϕ
$\left|\frac{F}{\rho g d^3 (X_o/d)}\right|$
$d\omega^2/g$

Figure 9.



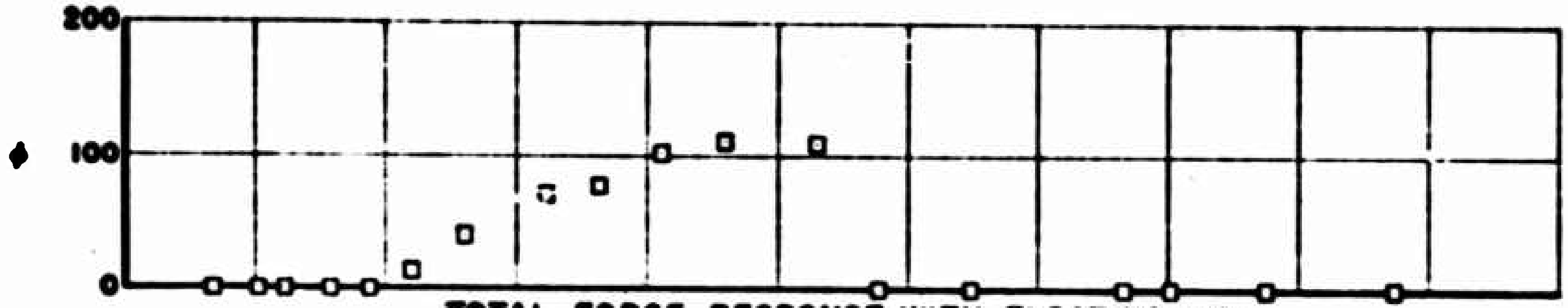
200
100
0
φ
TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 85% LID, h/d = 0.595
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 0.686 \cdot 10^6$
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
20
EXPERIMENTAL – X_o/d = 0.00417

Figure 10.

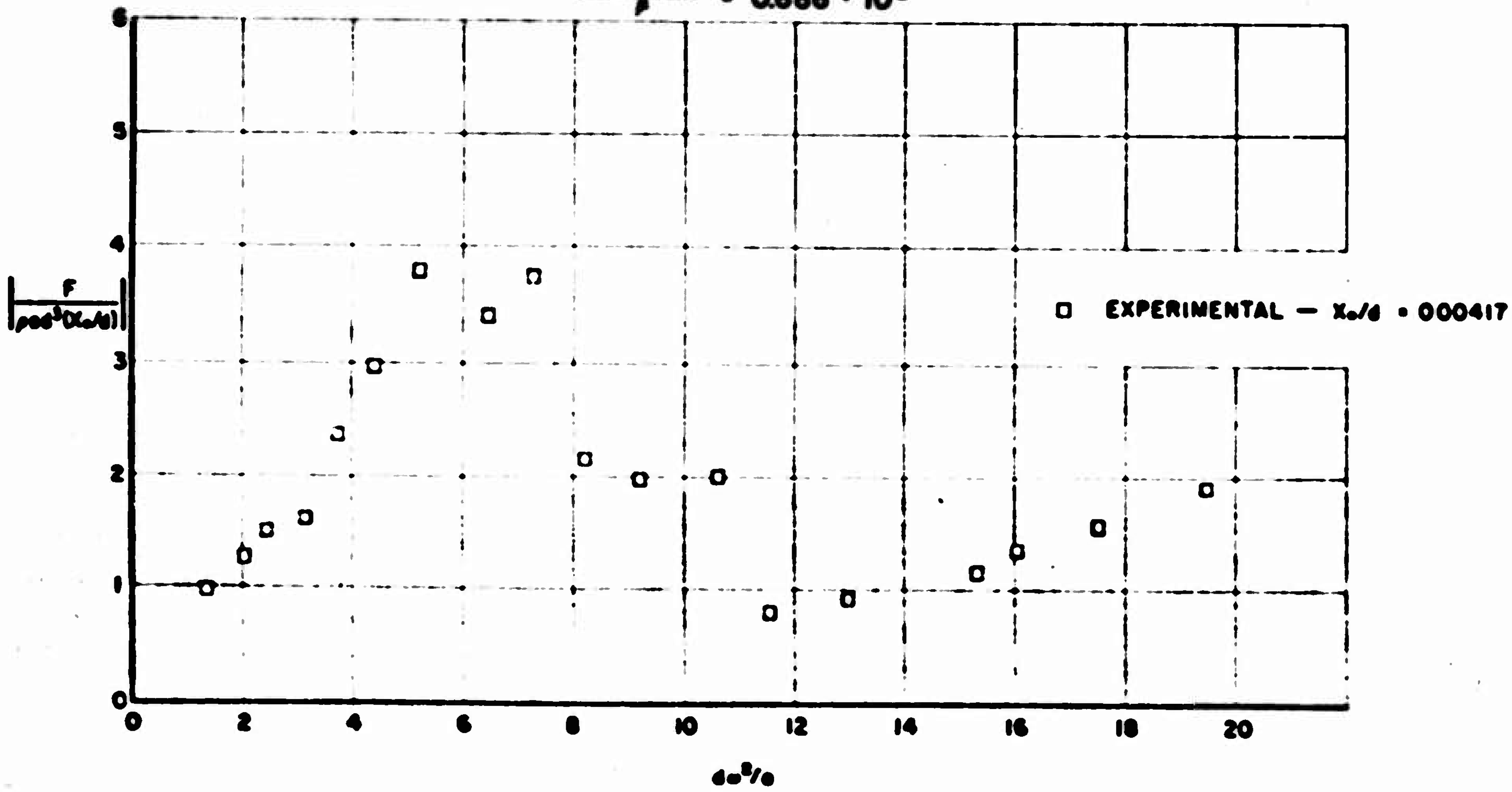


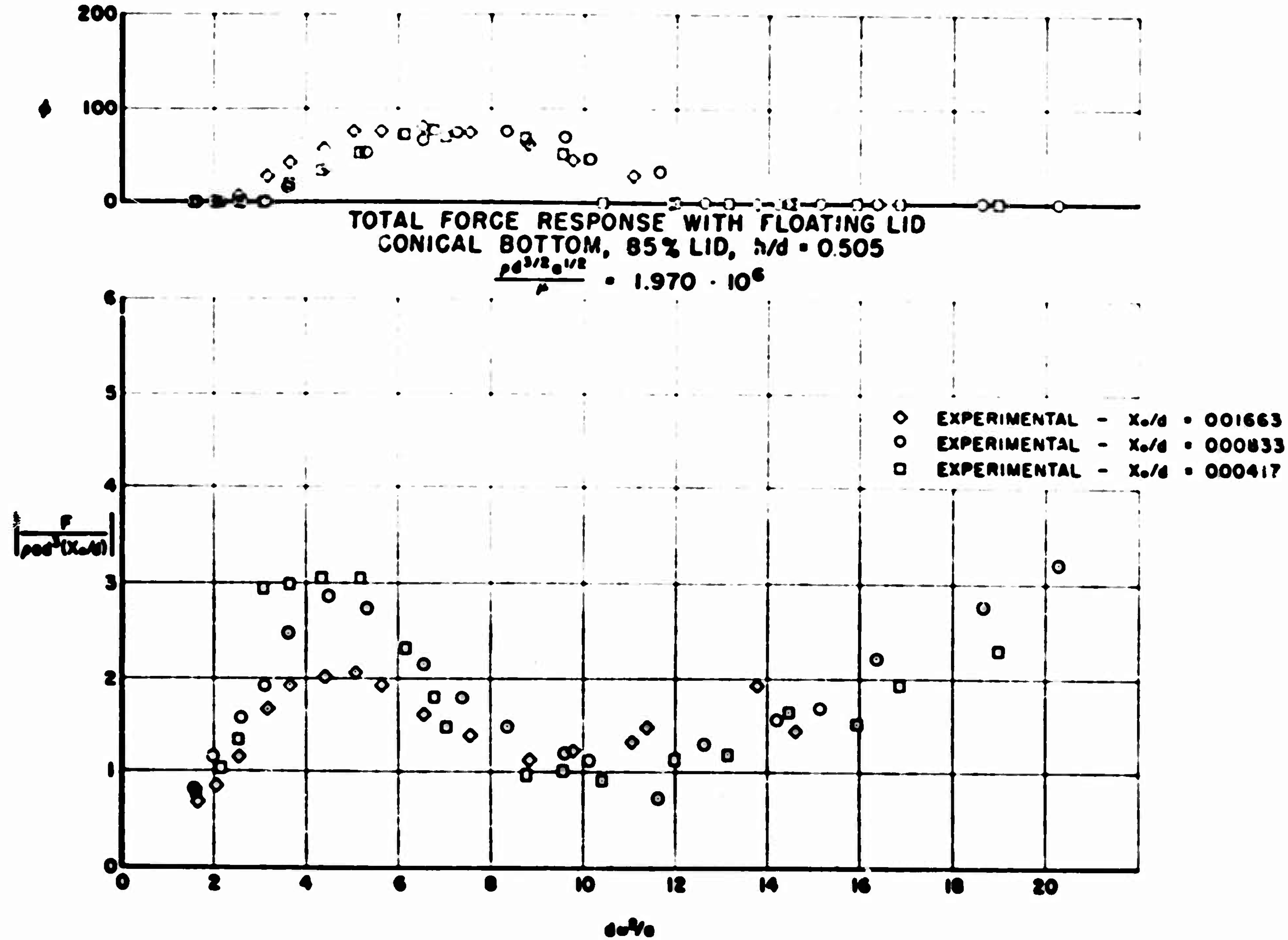
200
100
0
ϕ
TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 85% LID, h/d = 0.595
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
6
5
4
3
2
1
0
$\left|\frac{F}{\rho g d^3 (X_o/d)}\right|$
0
2
4
6
8
10
12
14
16
18
20
$d\omega^2/g$
EXPERIMENTAL — X_o/d = 0.01663
EXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417
EXPERIMENTAL — X_o/d = 0.00186

Figure 11.



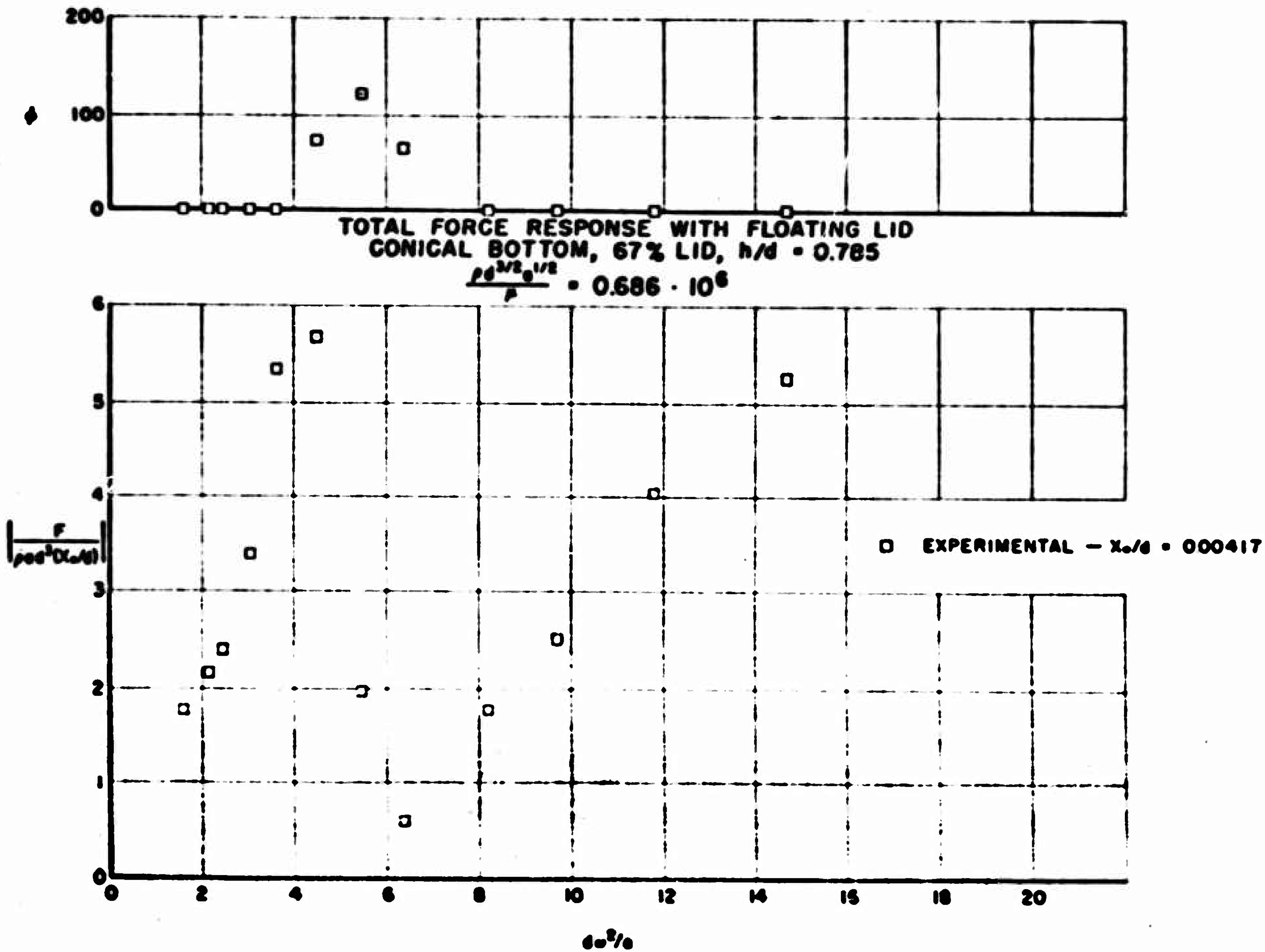
TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 85% LID, $h/d = 0.505$
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 0.686 \cdot 10^6$





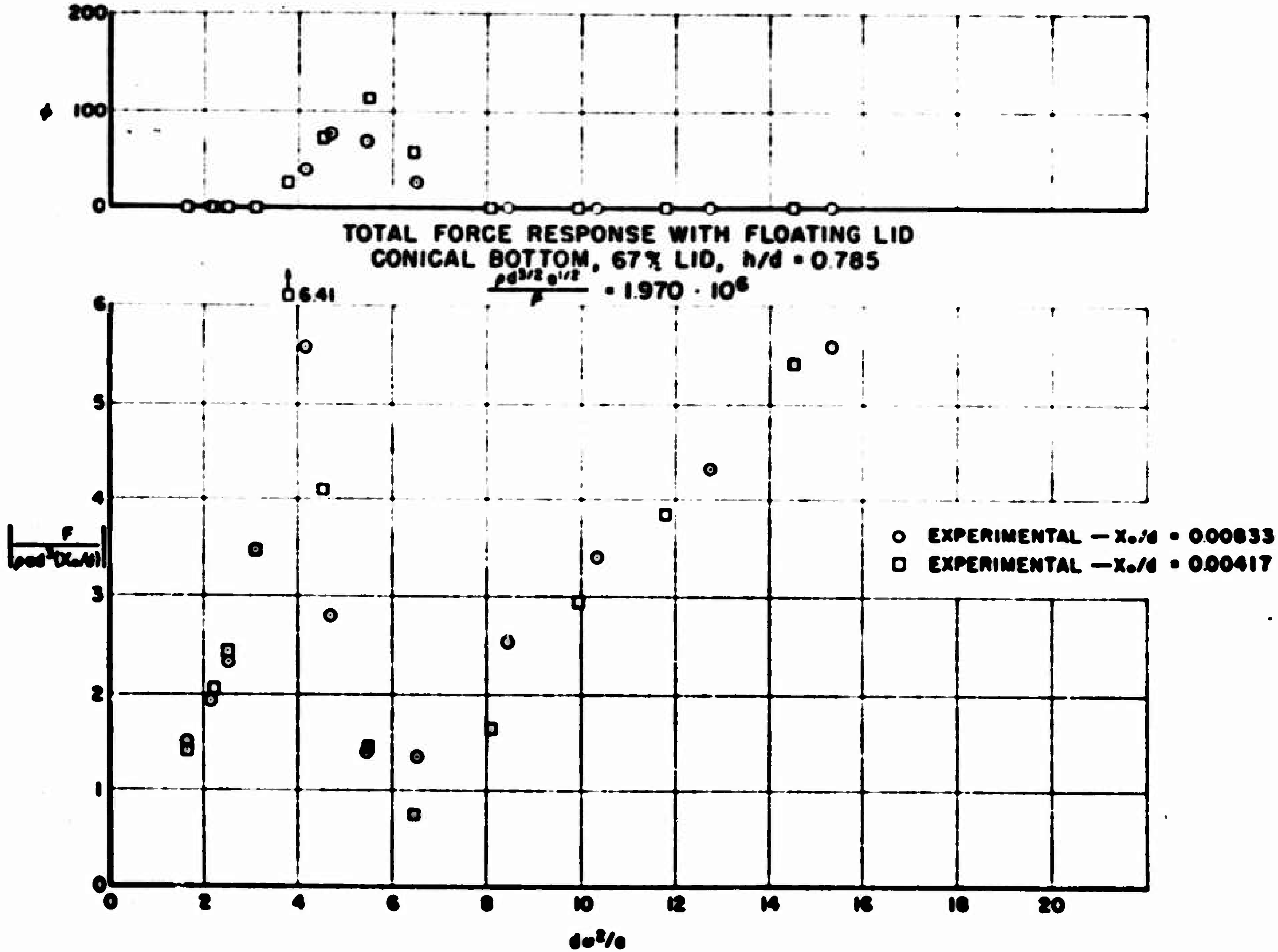
200
100
0
TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 85% LID, h/d = 0.505
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
6
5
4
3
2
1
0
EXPERIMENTAL - Xo/d = 001663
EXPERIMENTAL - Xo/d = 000833
EXPERIMENTAL - Xo/d = 000417
0
2
4
6
8
10
12
14
16
18
20

Figure 13.



TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 67% LID, h/d = 0.785
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 0.686 \cdot 10^6$
EXPERIMENTAL — X_0/d = 000417
ϕ
200
100
0
6
5
4
3
2
1
0
$\left|\frac{F}{\rho g d^3 (X_0/d)}\right|$
0
2
4
6
8
10
12
14
16
18
20
$d\omega^2/g$

Figure 14.



TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 67% LID, h/d = 0.785
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
6.41
ϕ
0
100
200
$\left|\frac{F}{\rho g d^3 (X_o/d)}\right|$
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
20
$d\omega^2/g$
EXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417

Figure 15.

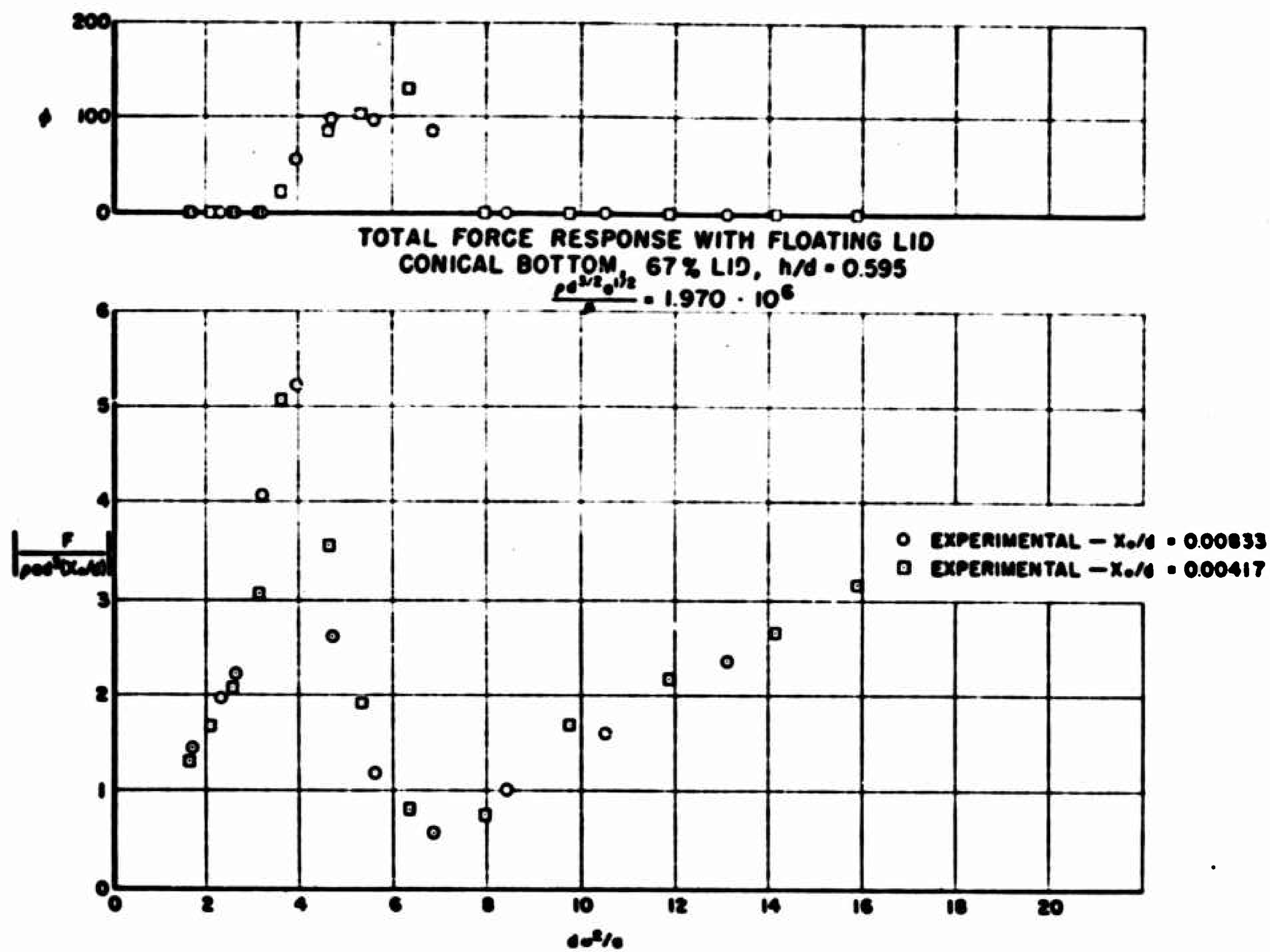

TOTAL FORCE RESPONSE WITH FLOATING LID
CONICAL BOTTOM, 67% LID, h/d = 0.595
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1.970 \cdot 10^6$
ϕ
200
100
0
6
5
4
3
2
1
0
$\frac{F}{\rho g d^3 (X_o/d)}$
0
2
4
6
8
10
12
14
16
18
20
$d\omega^2/g$
EXPERIMENTAL — X_o/d = 0.00833
EXPERIMENTAL — X_o/d = 0.00417

Figure 17.

Figure 17.

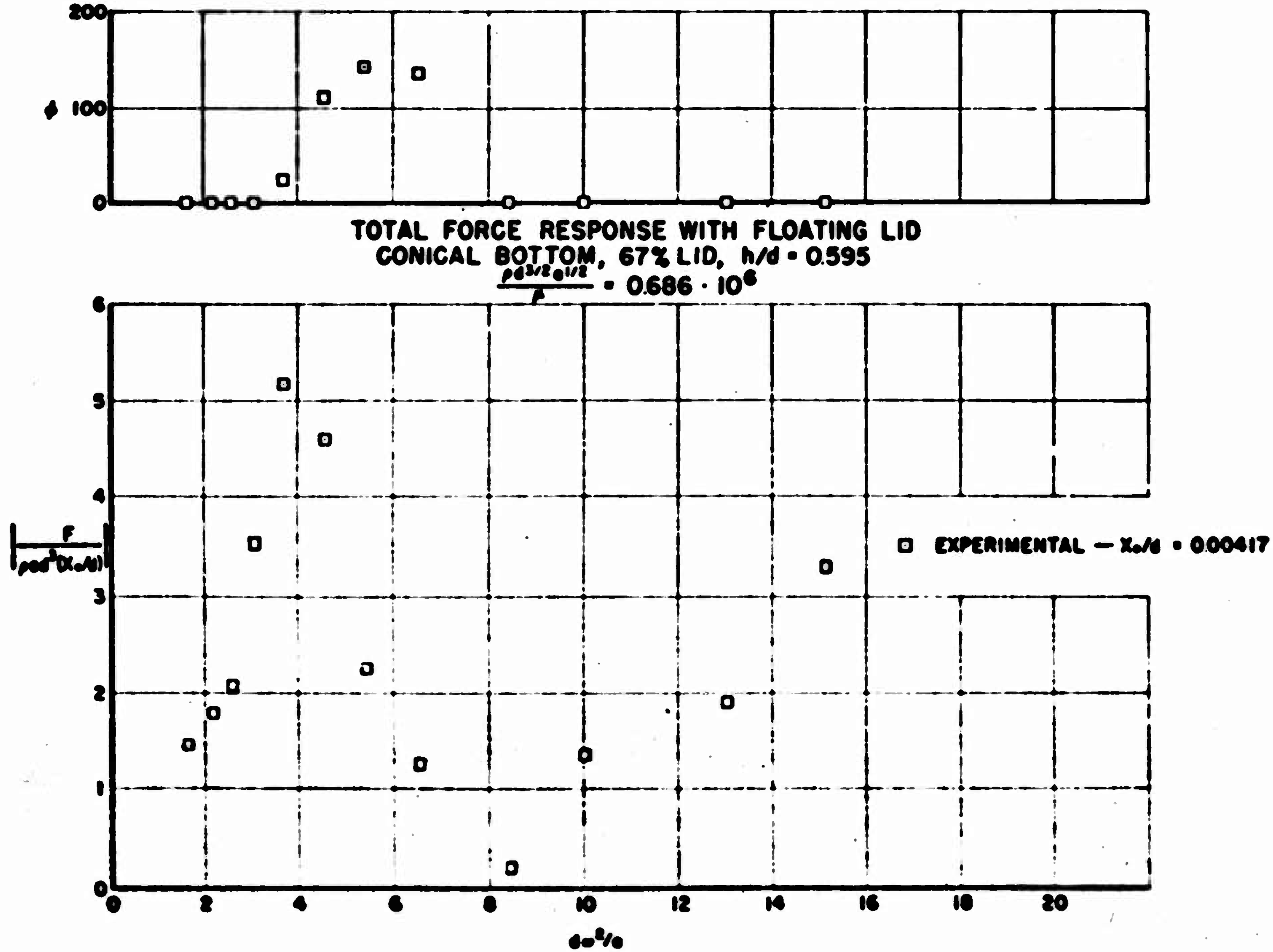
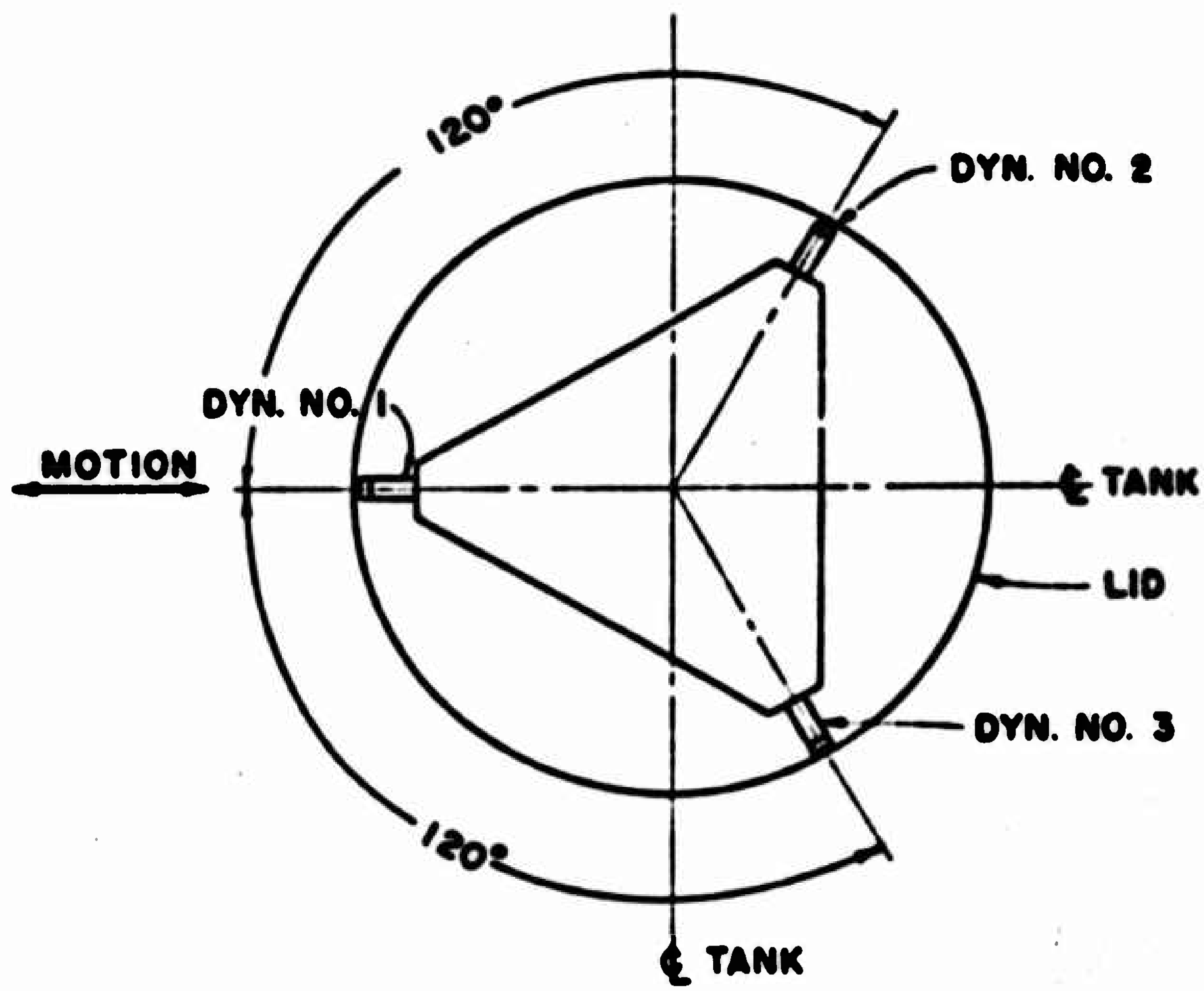


Figure 16.

LID DYNAMOMETER ORIENTATION



NOTE: FORCE ACTING UPWARD ON DYNAMOMETERS IS ASSUMED POSITIVE.

Figure 18.

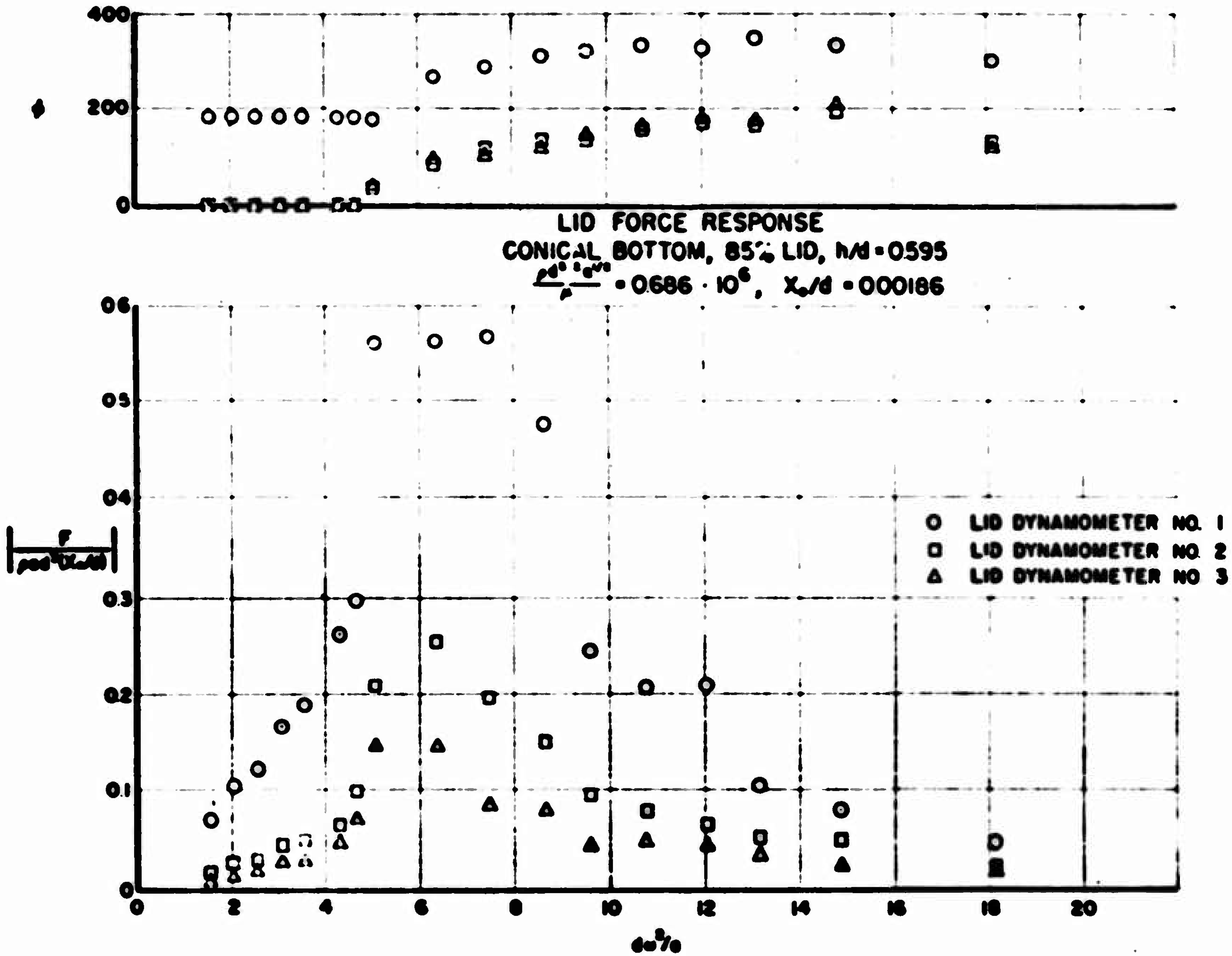
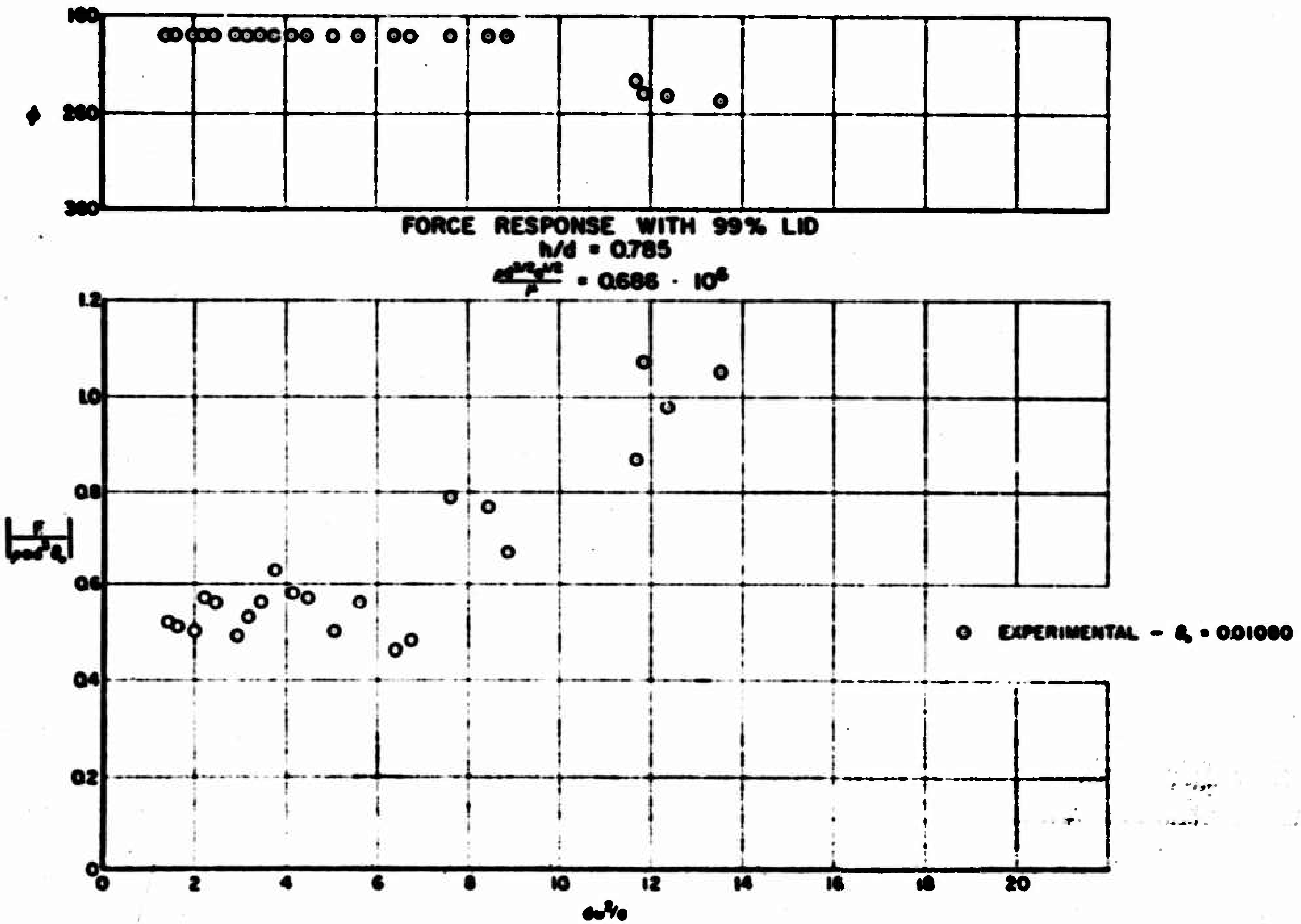
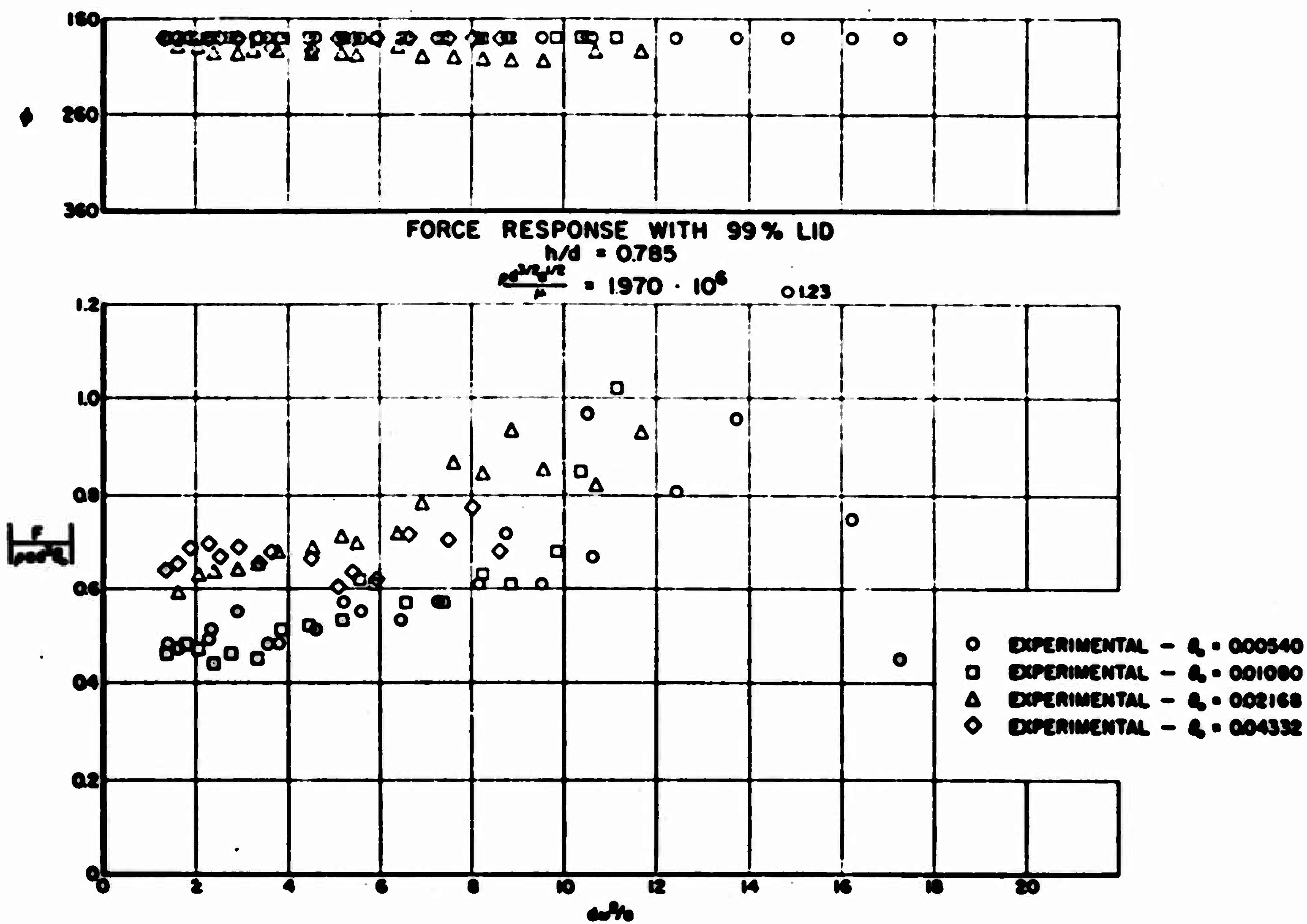

LID FORCE RESPONSE
CONICAL BOTTOM, 85% LID, h/d = 0595
$\frac{\rho d^2 \omega^{1/2}}{\mu} = 0.686 \cdot 10^6$, $X_0/d = .000186$
O LID DYNAMOMETER NO. 1
□ LID DYNAMOMETER NO. 2
△ LID DYNAMOMETER NO. 3

Figure 19.

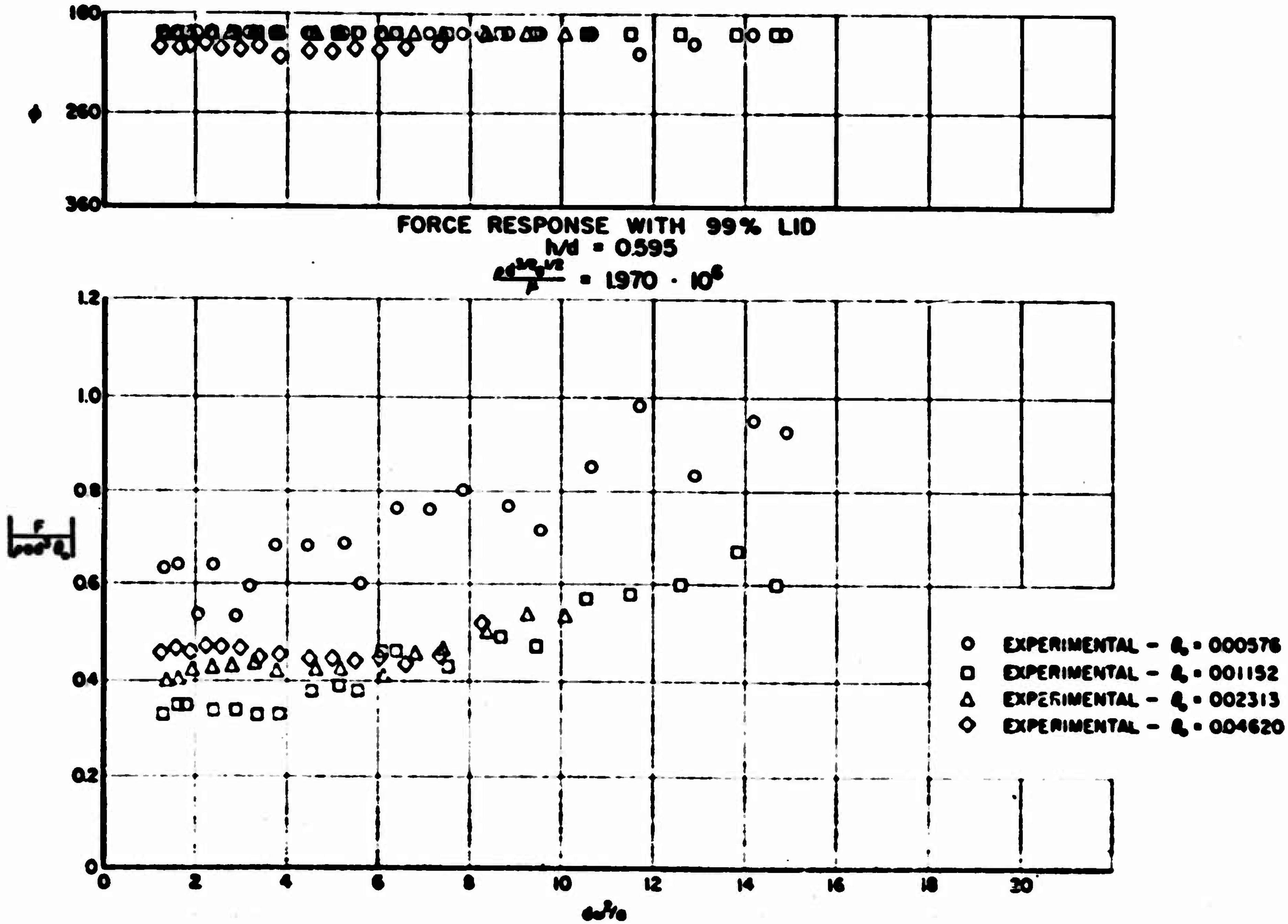


FORCE RESPONSE WITH 99% LID
h/d = 0.785
= 0.686 · 10⁶
EXPERIMENTAL
0.01080
0
2
4
6
8
10
12
14
16
18
20
0.2
0.4
0.6
0.8
1.0
1.2
100
200
300



FORCE RESPONSE WITH 99% LID
h/d = 0.785
= 1970 · 10^6
0.123
EXPERIMENTAL – = 0.00540
EXPERIMENTAL – = 0.01080
EXPERIMENTAL – = 0.02168
EXPERIMENTAL – = 0.04332
180
260
360
1.2
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
20

Figure 21.



FORCE RESPONSE WITH 99% LID
h/d = 0.595
= 1970 · 10⁶
EXPERIMENTAL − = 000576
EXPERIMENTAL − = 001152
EXPERIMENTAL − = 002313
EXPERIMENTAL − = 004620

Figure 22.

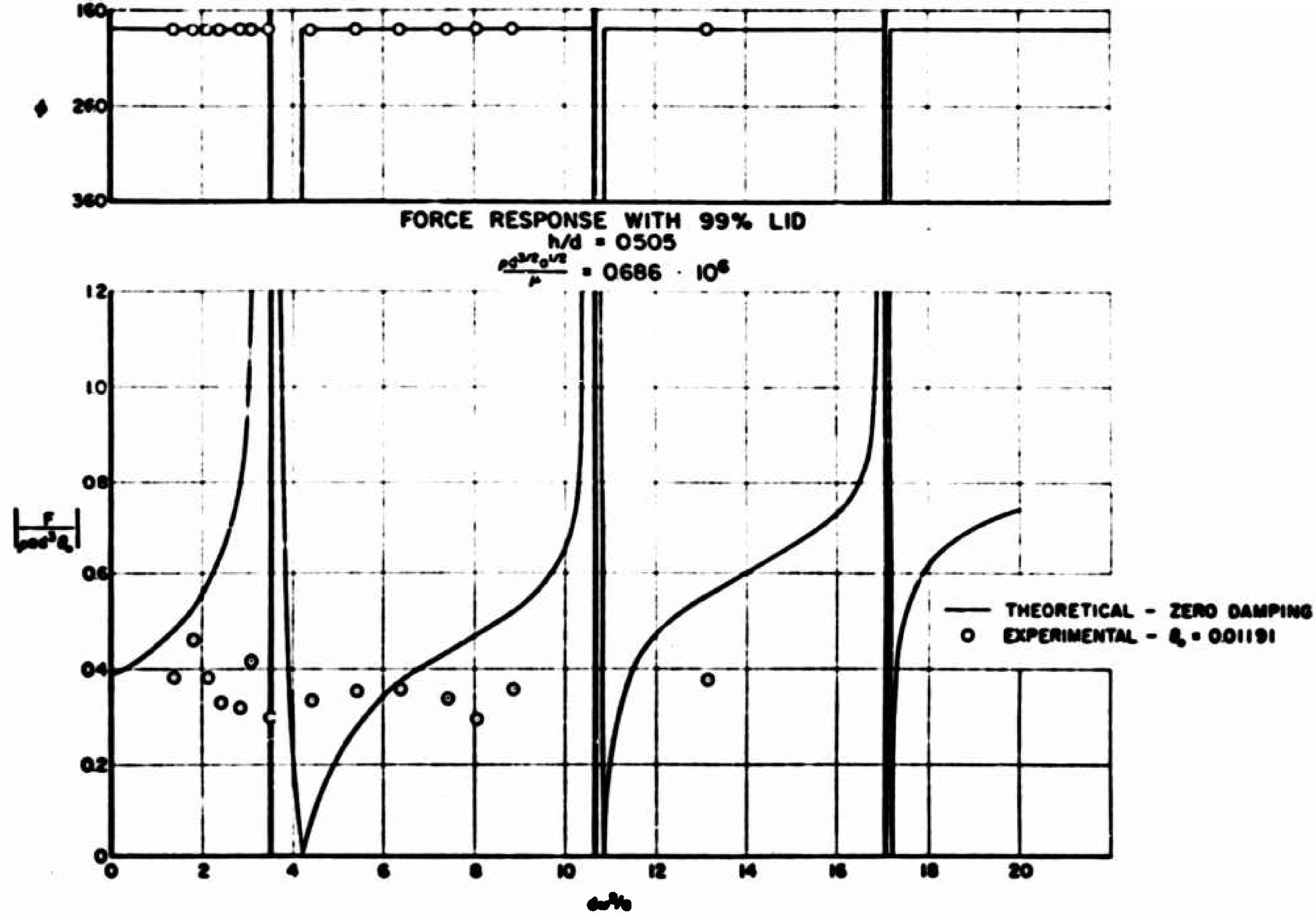

FORCE RESPONSE WITH 99% LID
h/d = 0505
= 0686 · 10⁶
THEORETICAL - ZERO DAMPING
EXPERIMENTAL - = 001191

Figure 23.

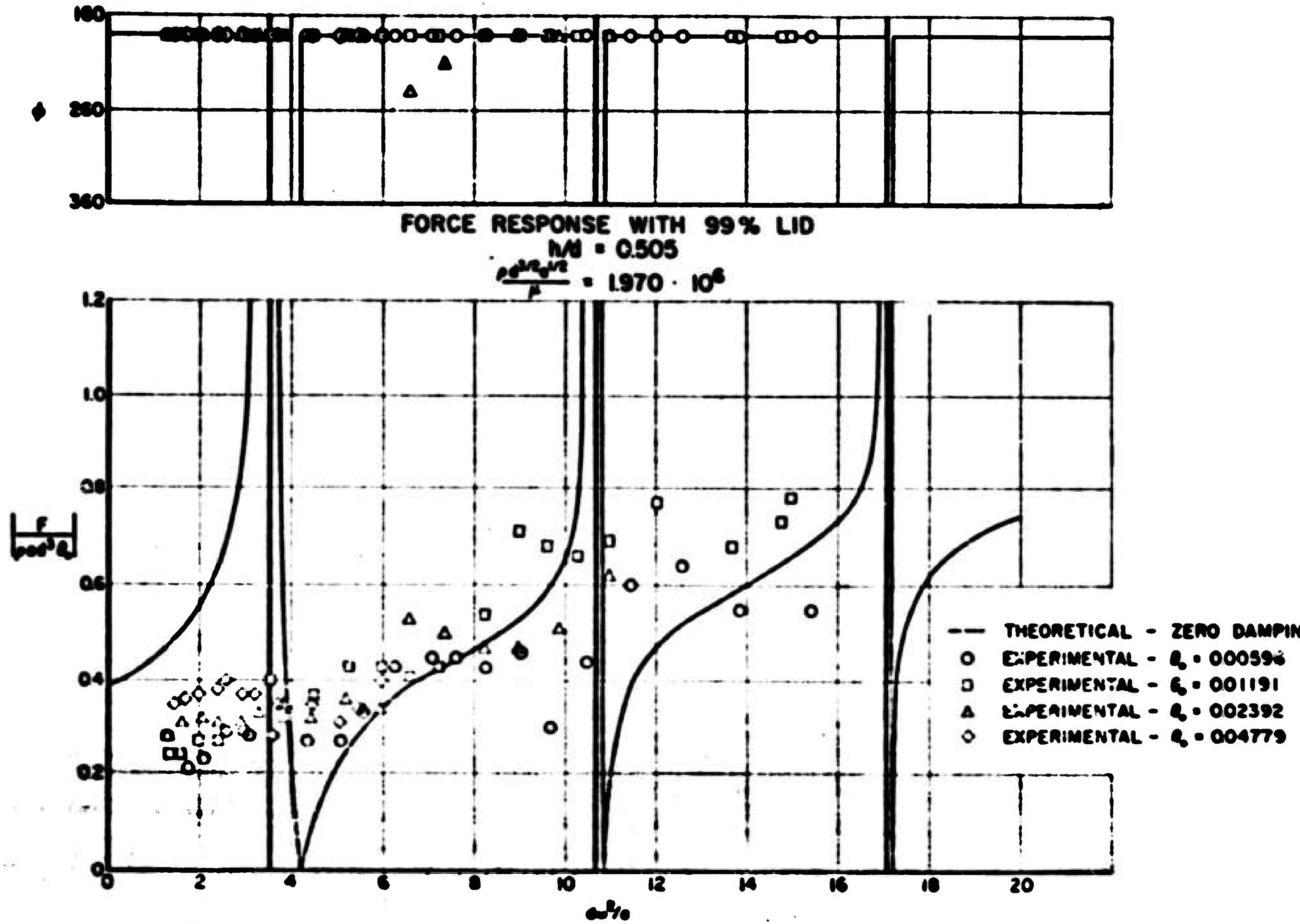
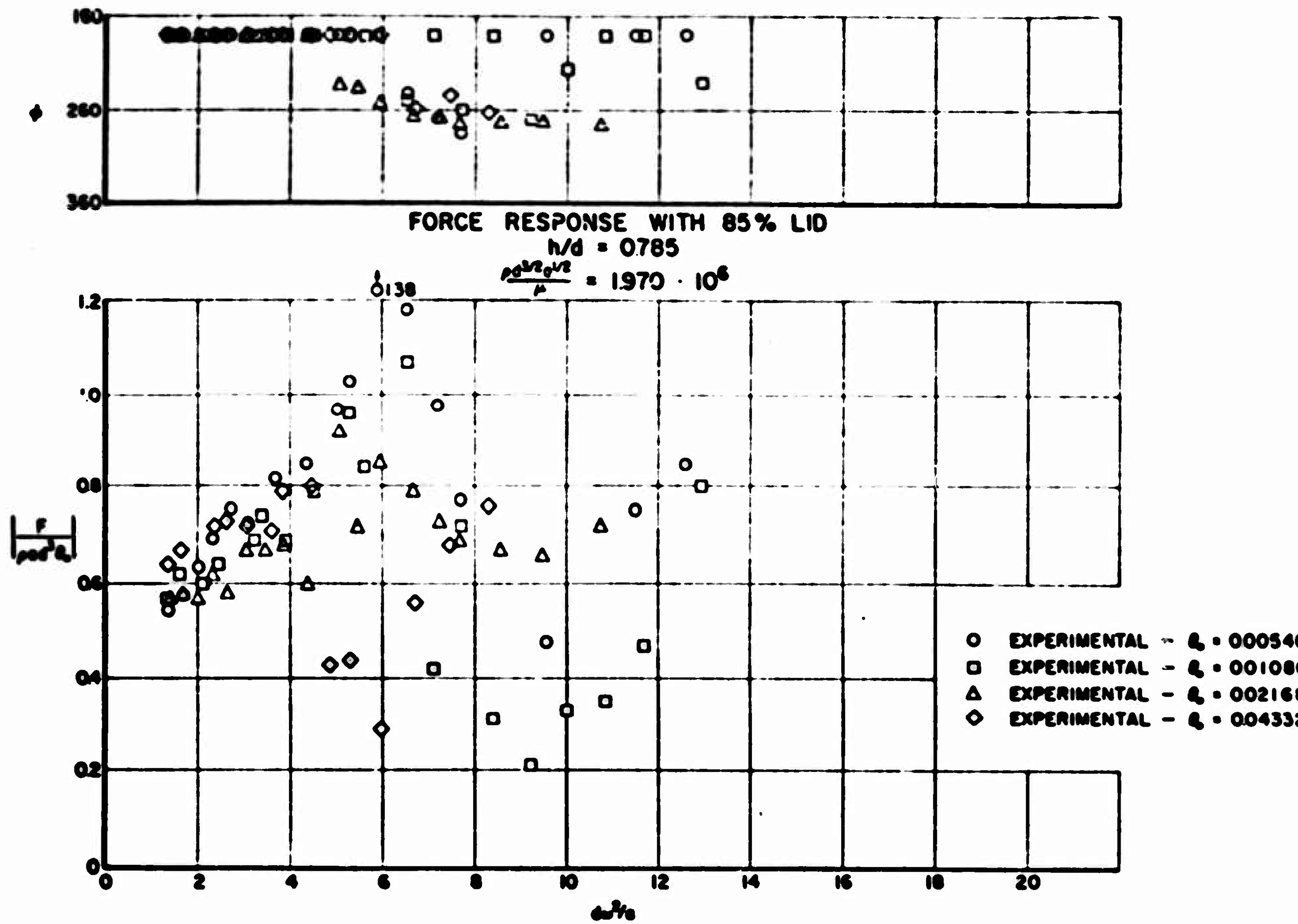

FORCE RESPONSE WITH 99% LID
h/d = 0.505
THEORETICAL - ZERO DAMPING
EXPERIMENTAL - θ_o = .000596
EXPERIMENTAL - θ_o = .001191
EXPERIMENTAL - θ_o = .002392
EXPERIMENTAL - θ_o = .004779

Figure 24.



FORCE RESPONSE WITH 85% LID
h/d = 0.785
$\frac{\rho a^{3/2} g^{1/2}}{\mu}$ = 1.970 · 10^6
0.138
EXPERIMENTAL – ϵ_0 = .000540
EXPERIMENTAL – ϵ_0 = .001080
EXPERIMENTAL – ϵ_0 = .002168
EXPERIMENTAL – ϵ_0 = .004332

Figure 25.

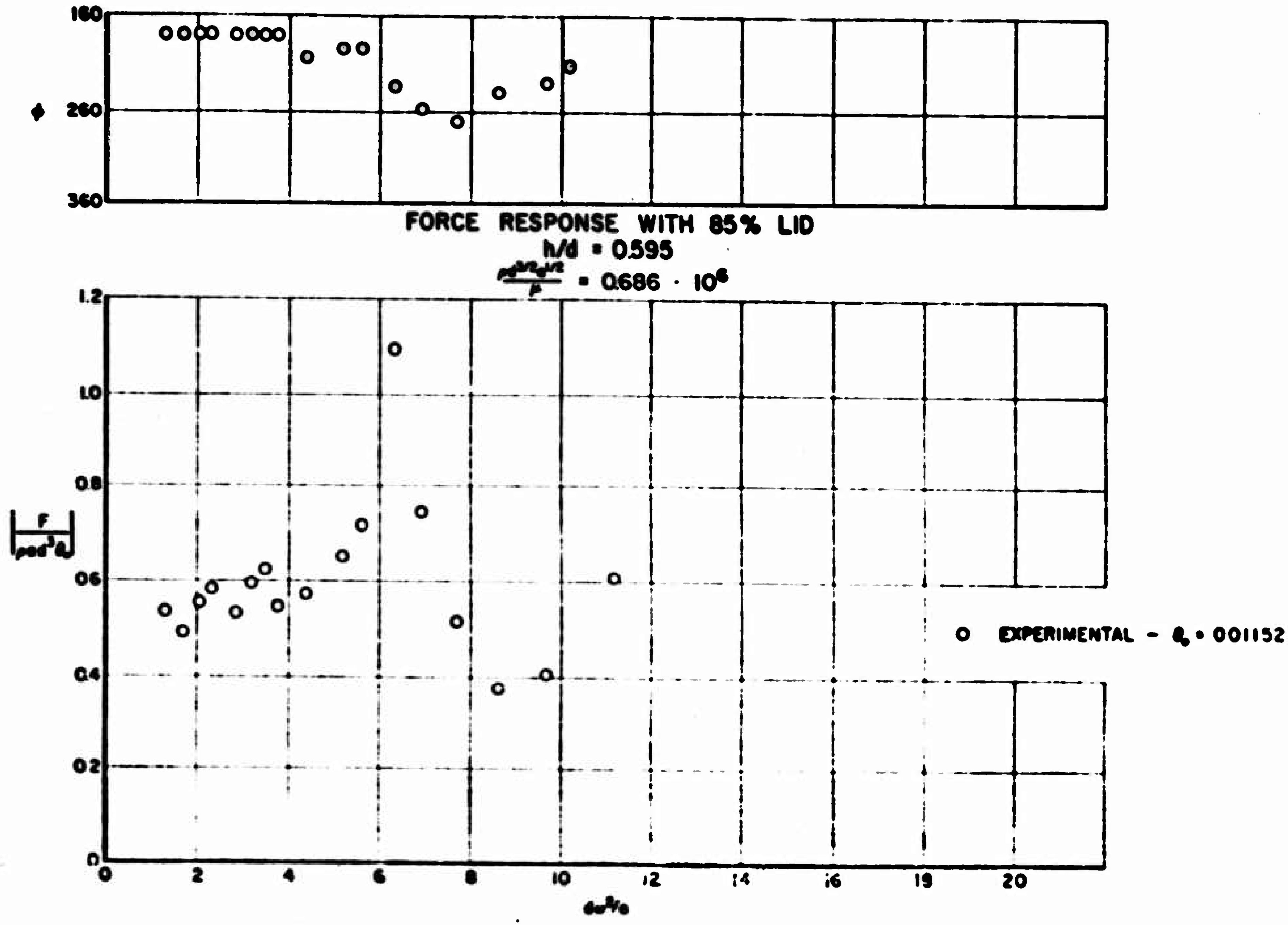
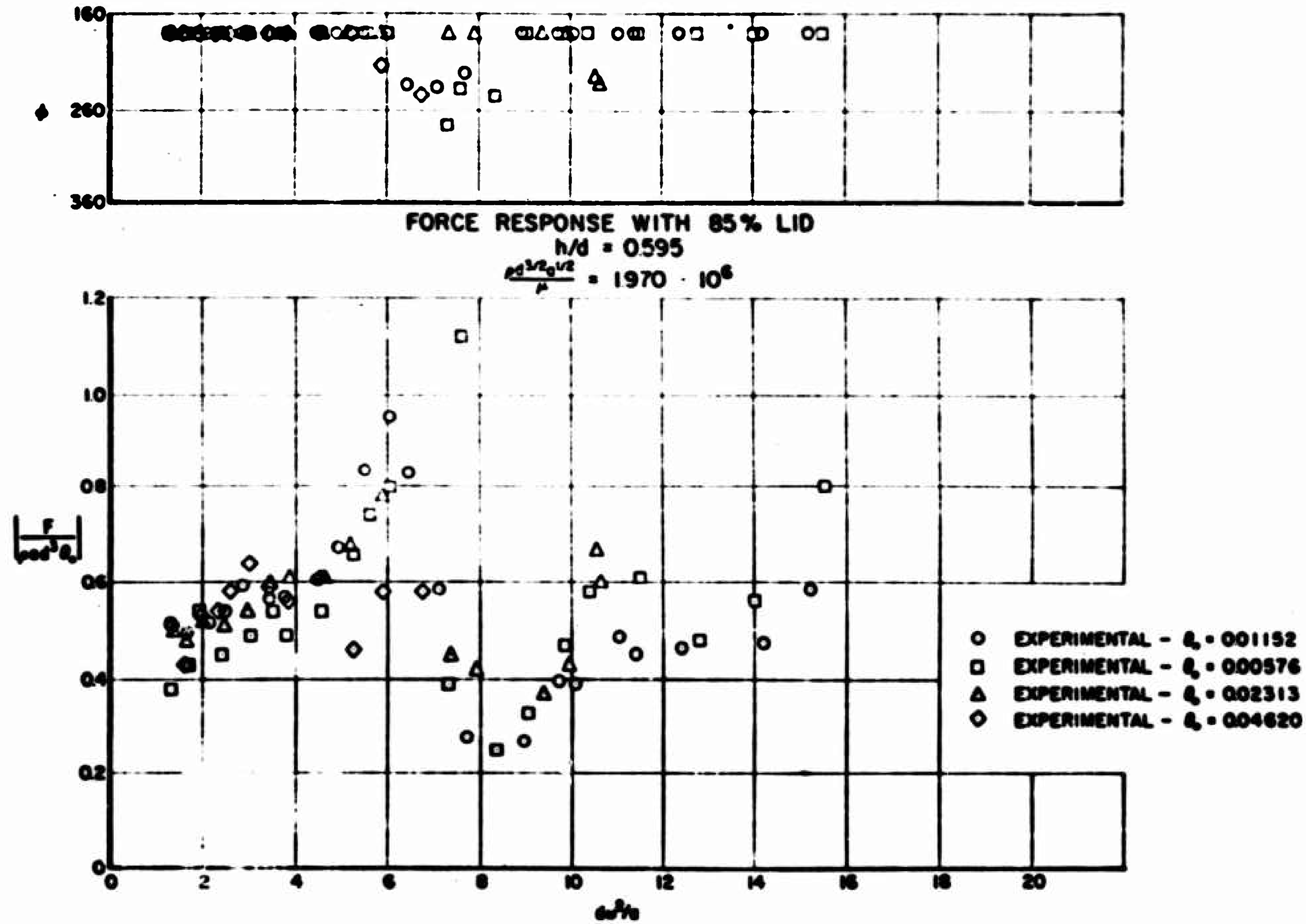
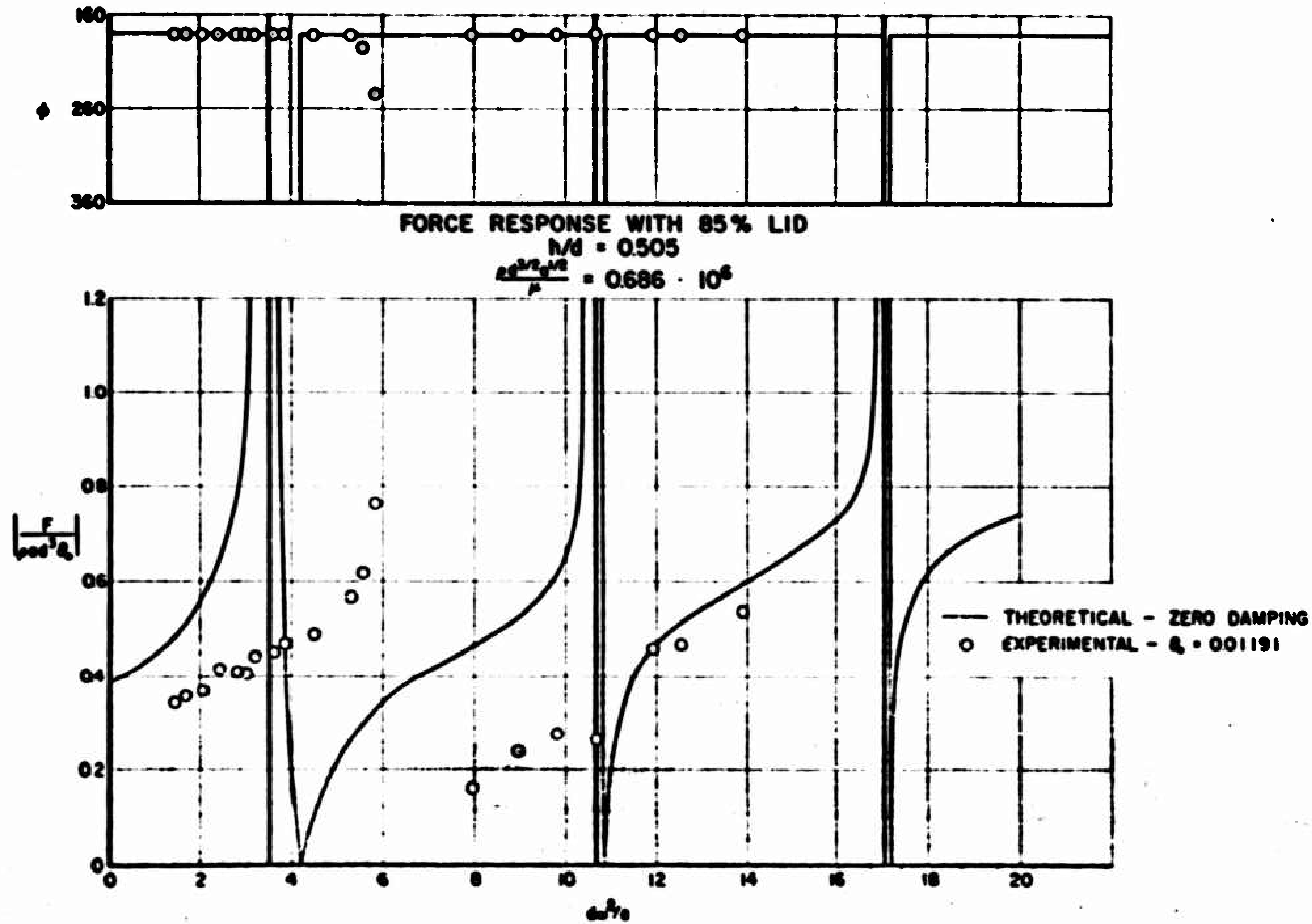

FORCE RESPONSE WITH 85% LID
h/d = 0.595
= 0.686 · 10^6
O EXPERIMENTAL - = 001152
180
260
360
1.2
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
20

Figure 26.

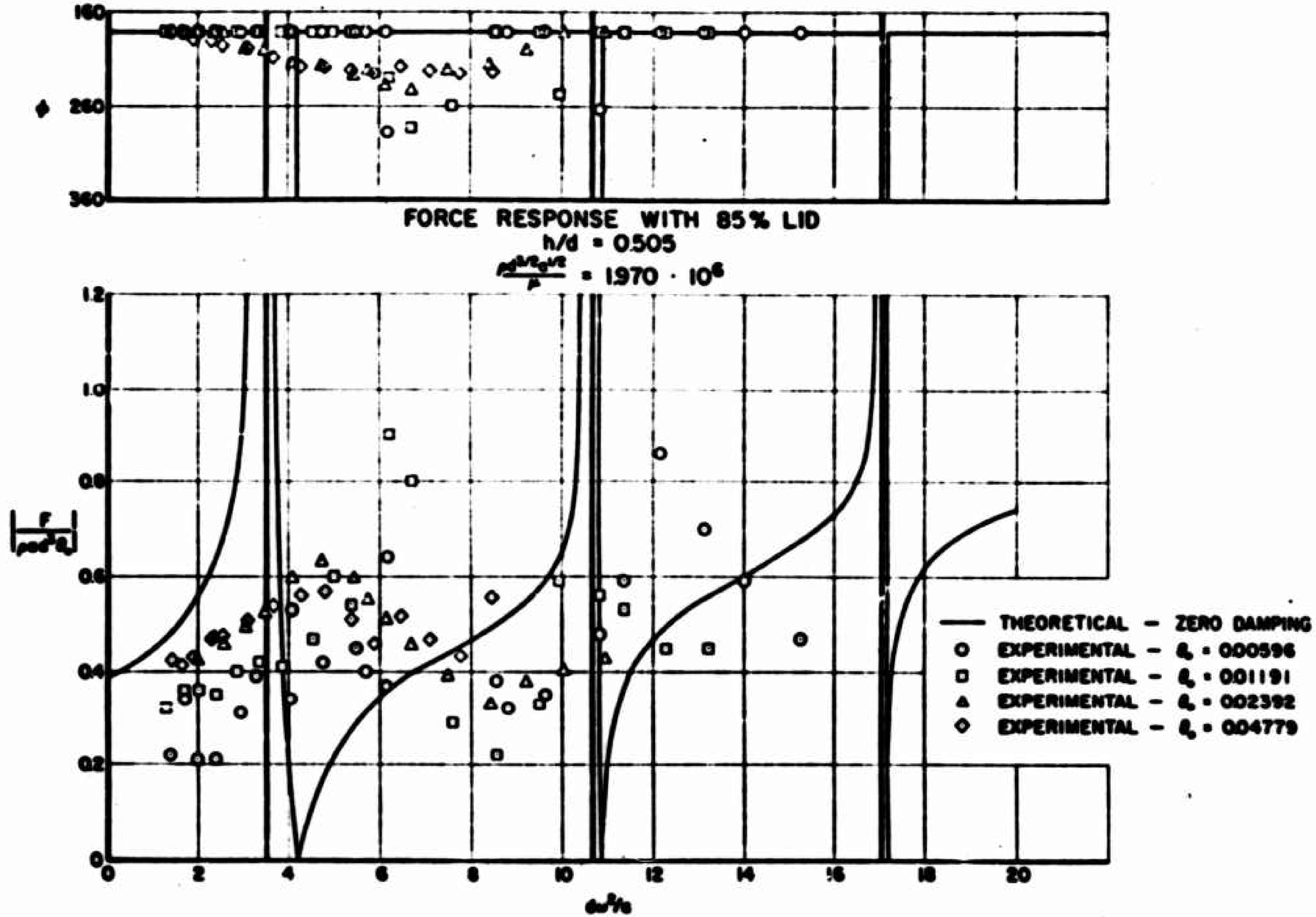


FORCE RESPONSE WITH 85% LID
h/d = 0.595
$\frac{\rho d^{3/2} g^{1/2}}{\mu} = 1970 \cdot 10^6$
160
260
360
ϕ
1.2
1.0
0.8
0.6
0.4
0.2
0
$\left|\frac{F}{\rho g d^3 \theta_o}\right|$
2
4
6
8
10
12
14
16
18
20
EXPERIMENTAL - θ_o = 0.01152
EXPERIMENTAL - θ_o = 0.00576
EXPERIMENTAL - θ_o = 0.02313
EXPERIMENTAL - θ_o = 0.04620

Figure 27.



FORCE RESPONSE WITH 85% LID
h/d = 0.505
= 0.686 · 10⁶
THEORETICAL - ZERO DAMPING
EXPERIMENTAL - δ₀ = 0.01191



FORCE RESPONSE WITH 85% LID
h/d = 0.505
= 1.970 · 10^6
φ
160
260
360
1.2
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
THEORETICAL – ZERO DAMPING
EXPERIMENTAL – θ₀ = .00596
EXPERIMENTAL – θ₀ = .01191
EXPERIMENTAL – θ₀ = .02392
EXPERIMENTAL – θ₀ = .04779

Figure 29.

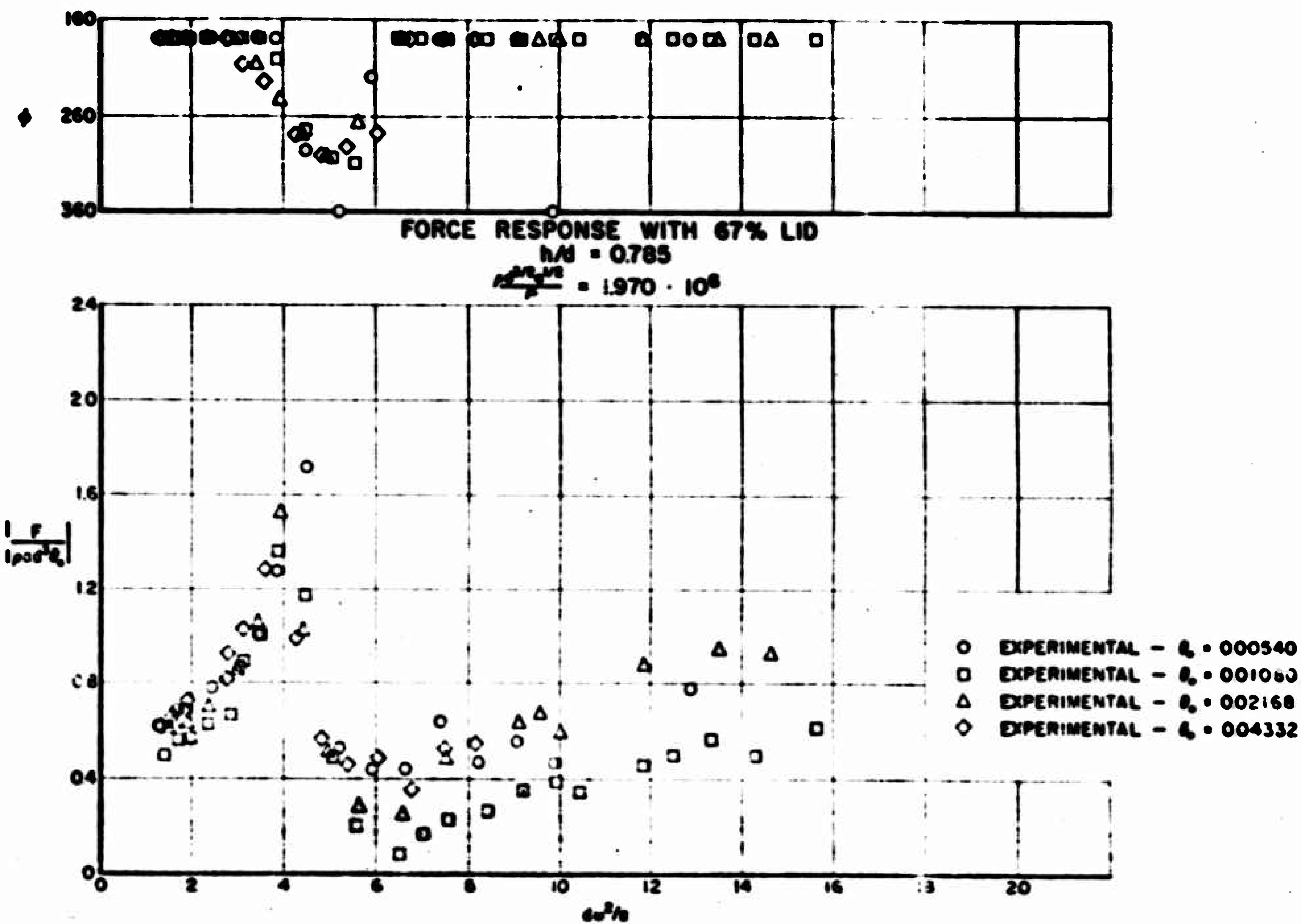

FORCE RESPONSE WITH 67% LID
h/d = 0.785
= 1.970 · 10^6
EXPERIMENTAL – = .000540
EXPERIMENTAL – = .001080
EXPERIMENTAL – = .002168
EXPERIMENTAL – = .004332
100
260
360
24
20
1.6
1.2
0.8
0.4
0
2
4
6
8
10
12
14
16
20

Figure 30.

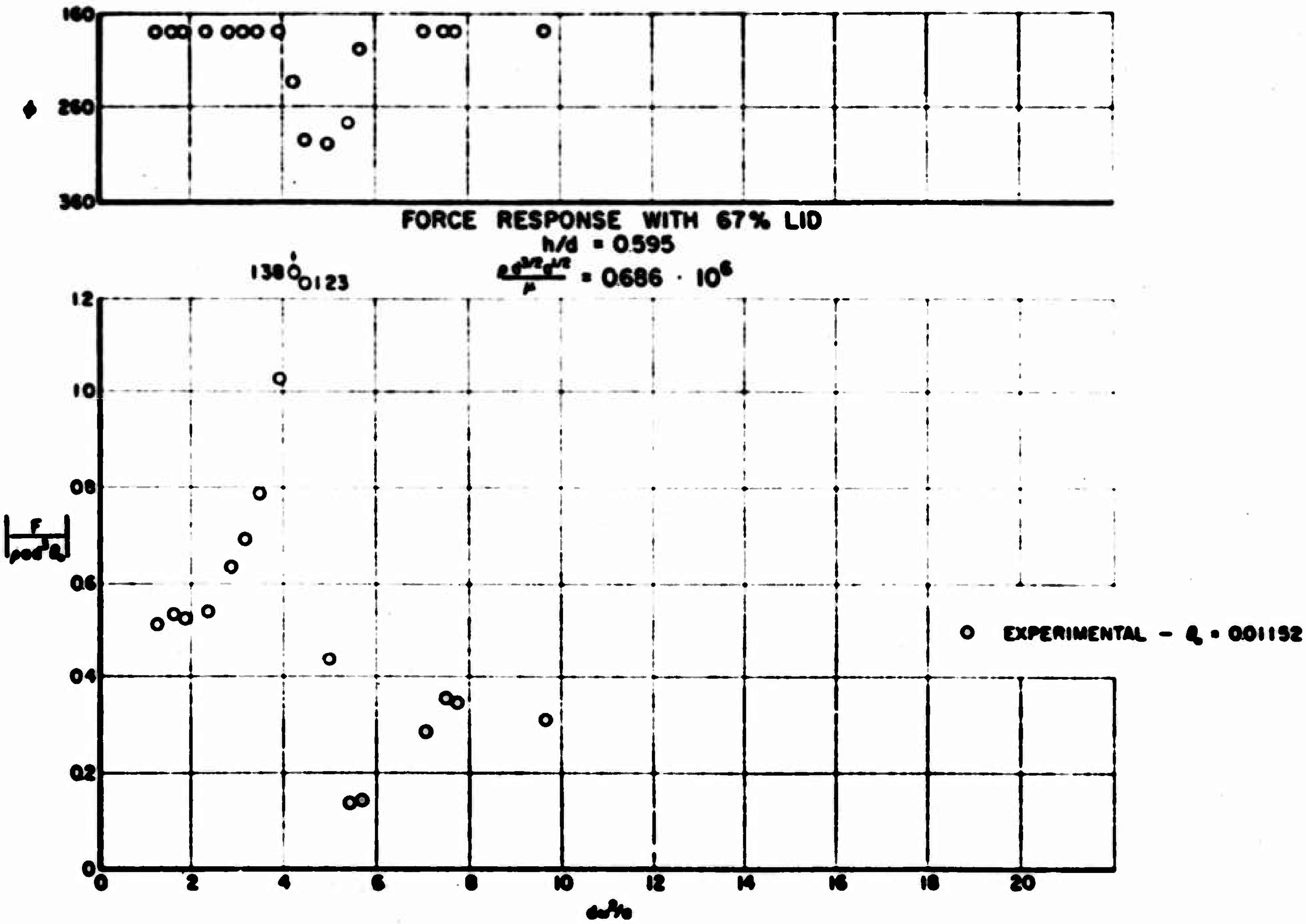
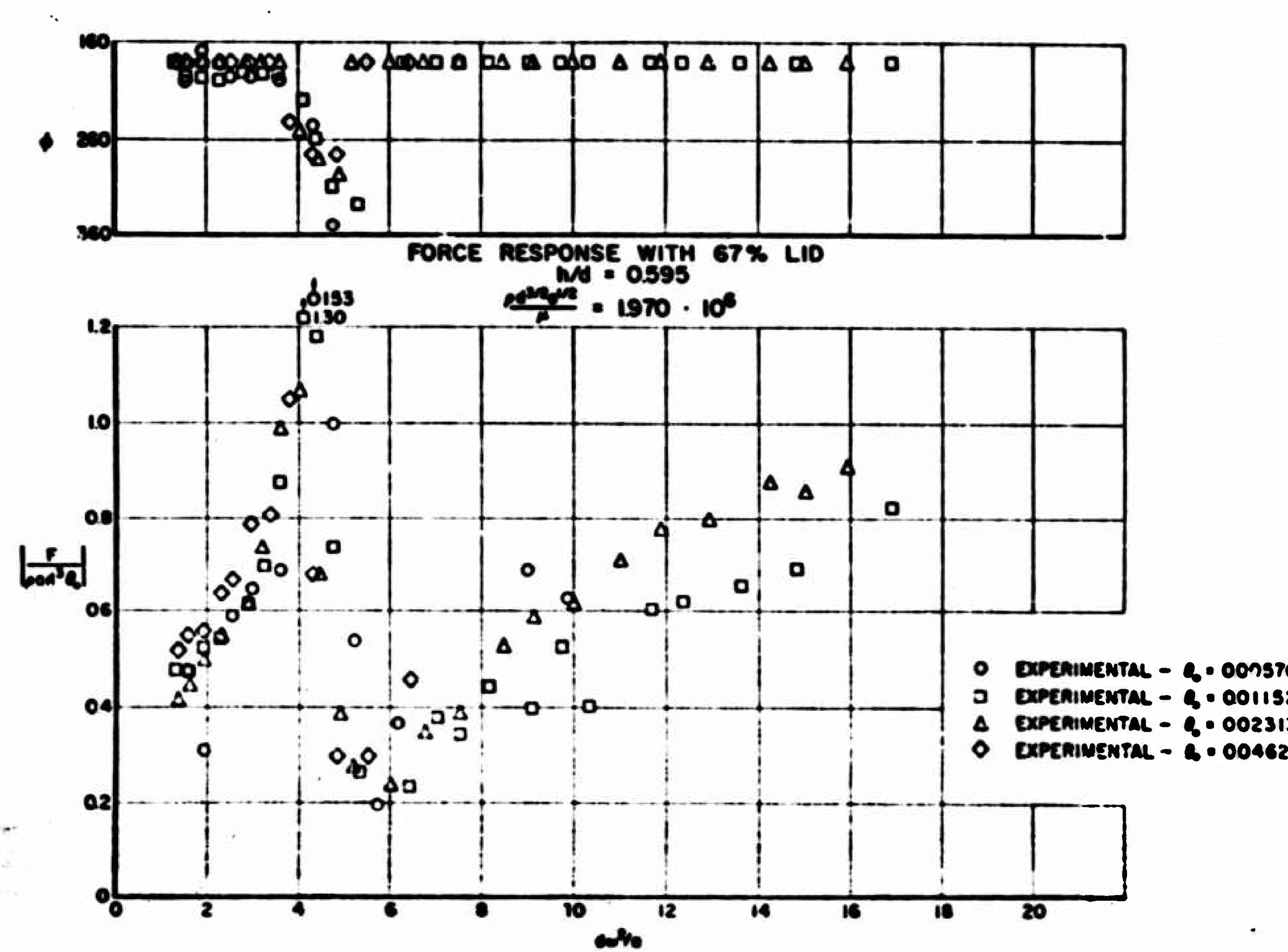
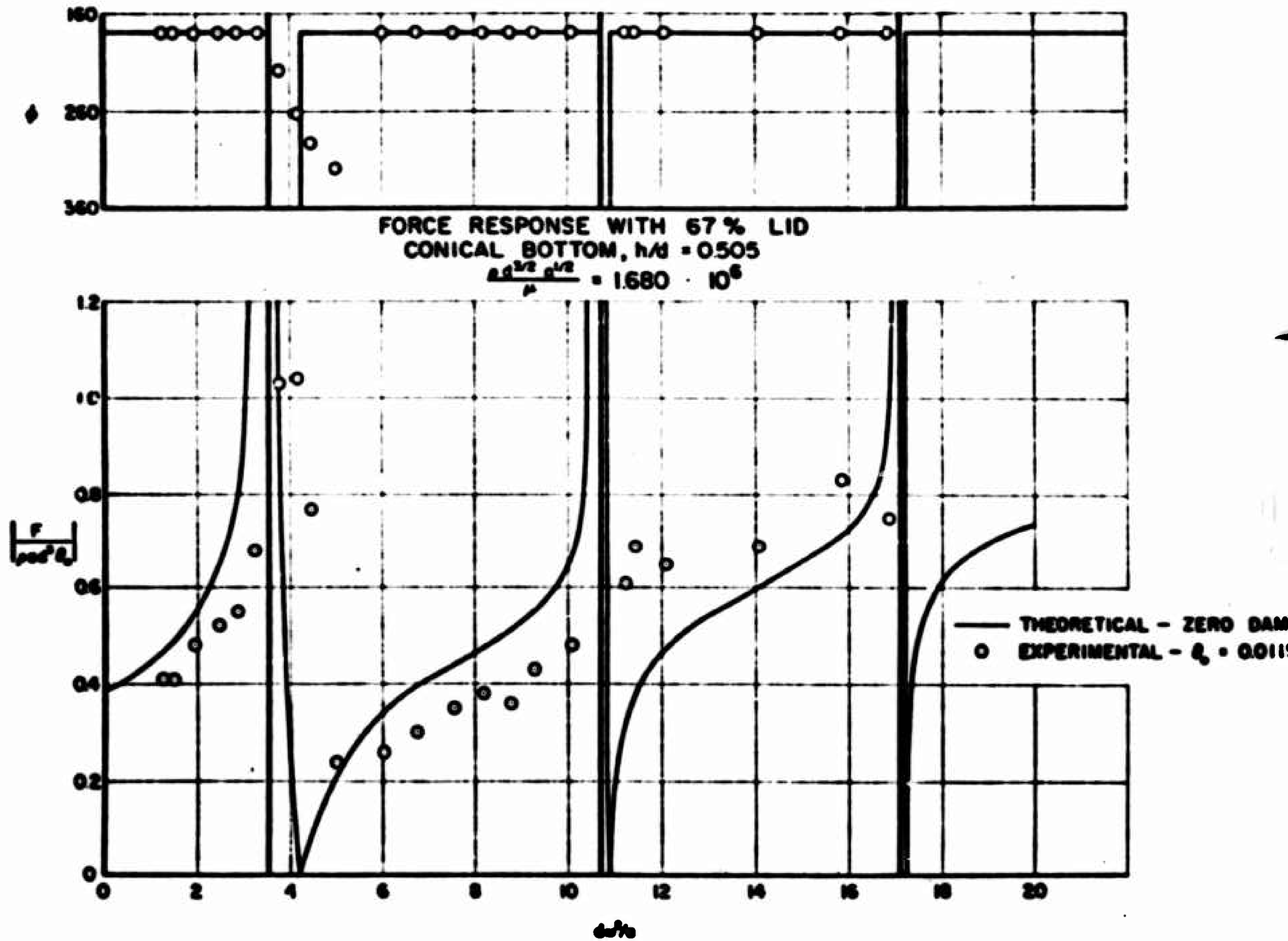

FORCE RESPONSE WITH 67% LID
h/d = 0.595
= 0.686 · 10⁶
138 0.123
EXPERIMENTAL - Q = 0.01152
160
260
360
1.2
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
20

Figure 31.



FORCE RESPONSE WITH 67% LID
h/d = 0.595
= 1970 · 10^6
EXPERIMENTAL - θ_o = .000576
EXPERIMENTAL - θ_o = .001152
EXPERIMENTAL - θ_o = .002313
EXPERIMENTAL - θ_o = .004620
.0153
1.30

Figure 32



FORCE RESPONSE WITH 67 % LID
CONICAL BOTTOM, h/d = 0.505
= 1.680 · 10^6
THEORETICAL - ZERO DAMP
EXPERIMENTAL - = 0.0115

Figure 33.